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Harmonic Distortion Analysis of a 200-MW Notional Solar Farm using IEEE Standard 519-2014

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Harmonic Distortion Analysis of a 200-MW Notional Solar Farm using IEEE Standard 519-2014

by

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Thesis

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Master of Science in Engineering

The University of Texas at Austin

May 2021

Dedicated

To all the folks whose name is considered a spelling mistake by MS word.

Acknowledgments

I would like to thank my supervisor, Surya Santoso, for this thesis; it would not have been possible without his exceptional support. His excellent knowledge of power quality and harmonics has paved my interest in this topic. His constant guidance has inspired me, keeping my work on track from my first class on this topic to the final draft of this thesis.

I am grateful to Professor Santoso for letting me work as his teaching assistant in the course Power System Apparatus & Lab, providing valuable insight into industry practices, and guiding me for my career after school. I would like to express my gratitude to Professor Hao Zhu for serving as a reader for this thesis and provide valuable knowledge through her courses at the University of Texas at Austin. I would also like to thank my colleagues at National Renewable Energy Laboratory, especially my supervisor Harsha Padullaparti, for providing valuable mentoring during my internship in electric distribution systems and motivation to conduct research. Working as an intern, I learned and applied essential research tools, which helped me complete this work.

Foremost, I would like to thank my parents for always believing in me and giving me the motivation to fly across half the globe to come to the US for higher education. I would like to sincerely thank my friends in Austin for supporting and being a part of my adventure trips.

Aaditya Sunil Kulkarni

The University of Texas at Austin, May 2021

Abstract

Harmonic Distortion Analysis of a 200-MW Notional Solar Farm using IEEE Standard 519-2014

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Solar farms are highly concentrated photovoltaic generation units located at the utility level. In this study, the impacts of harmonic distortions of a 200-MW notional solar farm were studied. A point of common coupling (PCC) is a common interface point between the utility and solar farm. Inverters are the primary component in solar farms injecting harmonic currents at PCC. The level of distortion is affected by various weather

conditions. This study primarily investigated irradiation impacts due to cloud coverage on the harmonic distortion.

These variations were classified as a clear, cloudy, and very cloudy week for analysis. A clear week means all clear days, a cloudy week means all cloudy days with good irradiance, and a very cloudy week means all cloudy days with low irradiance. IEEE standard 519-2014 version was used to analyze this impact by solar farms on the main grid. This standard requires conducting studies with stochastic nature of harmonic distortion, over at least one week, with different limits for various data percentiles.

A 200-MW notional solar farm inspired by real solar farms worldwide was modeled in OpenDSS. Inverters were modeled as current sources, injecting currents into transformers followed by collector circuits. Current injected by PV source was calculated from solar irradiation using an interpolation algorithm. Time-series simulations were performed using Python, with communication between OpenDSS and Python to analyze the impacts by the solar farm over a period. A simulation environment in Python was set up to perform the required functions for this study.

Observations reveal the dependency of distortion on irradiation and cloud cover. An increase in cloud cover means a reduction in irradiance. Validation of results was performed using few scenarios. Violations are defined as increases of voltage or current beyond the level specified by the standard. Odd order harmonics made voltage violations.

Current violations were made by even order harmonics only. Inverters were observed to inject a high proportion of harmonic current at lower irradiance. In conclusion, the studied 200-MW notional solar farm was observed to cause violations in a grid, with the nature of violations depending on irradiation and cloud cover.

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Chapter 1- Introduction

Renewable energy sources are the best way to tap into vast and abundant sources of energy. A solar farm is an efficient formation to tap this energy and generate power at a centralized level, acting like a power plant on its own.

Integration of solar farms into the power grid is a tedious task mainly due to its variable nature and scale. Problems arising in the power grid due to a single photovoltaic panel will be aggregate by solar farms. A solar farm is built from several photovoltaic arrays, which are connected to power lines through inverters. An inverter is a power electronic device significant in the contribution of harmonic currents. Inverters affect the grid in ways such as interference with communication networks and resonance conditions with capacitor banks. The essential process in building a new solar farm involves conducting studies for projecting such harmonic currents injected into the grid and planning for mitigation techniques.

Organizations like the IEEE have created guidelines for dealing with such scenarios, called standards. They are a set of numbers and methods around which situations in the power grid can be evaluated and mitigated. One of such standards released by IEEE in 1992 was Standard 519 [1]; this standard limits voltage and current distortions injected into the grid by industrial plants. The standard was not adequate to perform studies as they did not provide a clear view of violations at the common point of interaction. IEEE updated the standard in 2014 [2], with the requirement of operators and plant owners to perform statistical analysis over a period rather than the previous requirement of static nature.

This thesis aims to perform a study of a solar farm and understand the nature of harmonic voltage and current distortions injected at the common point of coupling with the utility system operator. Studies of such nature are usually performed by manufacturers and system operators, often not publicly available. Existing literature has studies of such nature that target the impact on the grid on aspects such as protection systems [3]. Assumptions such as inverters are significant contributors of harmonic emission are widely existing [4]. Studies focusing on harmonic injections and analysis such as network resonance conditions [5] are present. They discuss the impact on distribution feeders in Canada and shed light on resonance conditions for various scenarios.

Studies emphasizing using IEEE standard 519 are less available; one such study [6] has analyzed the impact of the solar farm using the 2014 version of standards. This study lacks information on the modeling of solar farms and simulation techniques used to evaluate the limitations imposed by standards. An analysis performed in this thesis solves the problems present in existing literature, and an effort on transparency about every aspect of the study is made.

In Chapter 2, several aspects of various solar farms are discussed, followed by an in-depth discussion on designing a generic solar farm involving parts such as inverters and material in solar arrays. A detailed process of developing a generic solar farm was followed, inspired by work such as [7], which discusses the design and construction of a solar farm.

In Chapter 3, a discussion on the introduction of harmonics was done, which was developed based on literature [8]. Harmonic standards 519 was explained with differences between the 1992 and 2014 versions, followed by harmonic measurements used in this work. Detailed discussion on percentiles and their calculation was performed, mainly due to the standard statistical analysis requirement. Further in the chapter, the limits recommended by standards were discussed. As inverters are the primary source of harmonic distortions in our system, a detailed discussion was performed at the end of the chapter.

In Chapter 4, a discussion on modeling and simulation techniques was done. Modeling and simulations are the backbones of this study. The chapter starts with a description of tools such as OpenDSS and Python, which were extensively used. Following a discussion on solar irradiation and details on the dataset used for the study, different types of irradiance profiles like a clear week, cloudy week, and very cloudy are defined for better understanding our problem.

Discussion is further advanced into modeling methods for inverters, followed by a description of the interpolation algorithm used to find the corresponding current injections. The chapter extends into giving a glimpse into the actual solar farm used in this study, followed by in-depth details on the simulation algorithm used to carry out time-series analysis of harmonic current contributions. Discussion in this chapter is concluded with the interconnection transformer and its validation techniques. As solar farms are connected to the main grid with the help of an interconnection transformer, modeling such elements should be accurate. Hence, validation techniques are used to determine the accuracy of the model.

Results and analysis are presented in Chapter 5, where data visualization techniques were used to have a clearer idea about numbers and what they represent to this study. The chapter starts the analysis with percentile charts, visualizing violations caused by various harmonic frequencies and their current and voltage contributions, followed by validation for results with the help of few scenarios. Line charts for voltage and current distortions are explained later. The chapter then advances into the calculation of total demand distortion and total voltage distortion.

Chapter 6 deals with providing a conclusion to the above study. One of the crucial questions in this study is investigating the dependence of harmonic distortion on the nature of cloudiness. This chapter advances into finding critical takeaways from this study and a commentary on how it compares with existing literature. The discussion is concluded by offering suggestions and possible mitigation techniques with possibilities of future work evaluated.

Chapter 2: Renewable energy generation and solar farm

Renewable energy is derived from sources that have an abundance of that source causing energy generation. For example, solar energy is renewable because the Sun shines throughout the year with no limit on irradiation. Similarly, wind energy is generated by the wind, which is a never-ending phenomenon on earth. Solar farms are an essential part of this energy ecosystem; hence our study will be focusing on energy generation from solar farms. In this chapter, we will review some fundamental foundations of solar farms and critical aspects included in the actual working of a solar farm. We will dive deeper into designing a generic solar farm for our study, inspired by real solar farms.

2.1 Introduction to Solar Farms

The world is moving towards adopting more renewable energy generation into power grids for several reasons like carbon neutrality, profits, or limitations caused by the fossil industry. However, the form and nature in which these energy sources are present create a problem for power grids, mainly due to their stochastic nature and the type of currents they produce. For example, energy generated from a wind turbine is variable. Hence it is always hard to predict the generation by windmills. Similarly, solar radiation may mostly be predictable, face the problem of being generated as DC sources. The power grid on the other side is predictable and balanced. Hence converting this variable nature source require various types of devices such as cyclo converters, rectifier, and inverters. These conversion units are power electronics; they increase the efficiency of specific processes but generate other issues like generating harmonics. Power electronics converters generate non-sinusoidal waveforms which are none other than harmonics and may severely impact the power grid.

Solar farms, technically called photovoltaic power stations or utility-scale solar plants, are large-scale photovoltaic systems designed to supply power on sub-transmission-level or utility [9]. They generally supply power at the utility level and often come under transmission operators or ISOs. Most solar farms lie at the transmission level, and they must follow the regulations and limits of high voltage levels, often 133 kV and higher. Declining costs of PV technology, coupled with government policies targeting large-scale renewable energy, has made utility-scale solar more competitive to other forms of decentralized electricity generation, driving rapid deployment in many countries across the globe. Due to the large scale of these solar systems, the processes involved in developing these projects are far more complex and rigorous than those for more minor, decentralized PV systems [7]. As a solar farm is merely a large picture magnification of a small PV cell, every problem a PV cell faces will be magnified. For instance, a small PV cell that generates DC power must be converted using inverters into AC power. However, in the process, it will generate non-sinusoidal components in the form of harmonics. As there are many PV cells in solar farms, there will be a sizeable harmonic current injected in the grid, generally at the transmission level, and will travel to generators and distribution circuits. Solar farms as a generation unit are a way to use than any other centralized power generators because of the following reasons:

- Use of land beneath PV arrays for purposes like agriculture.
- Possible construction on contaminated or barren land.
- Reclamation of land at the end of the commissioning period.

Fig 1: A commissioned solar farm (image courtesy of Solar DAO)

2.2 Design of a General Solar Farm

Major components of a solar farm include [7]:

- PV Arrays
- Inverters
- Reactive Power Control
- Protection Systems
- DC/DC Converters

- Interconnection Transformer
- Cables

These components are discussed in detail as below:

PV Array: an array is a combination of multiple PV cells in a particular combination. A combination of modules in series will create a higher voltage, whereas a combination in parallel will create a higher current. Such combination is together called a PV Array. A general PV array is shown as below:

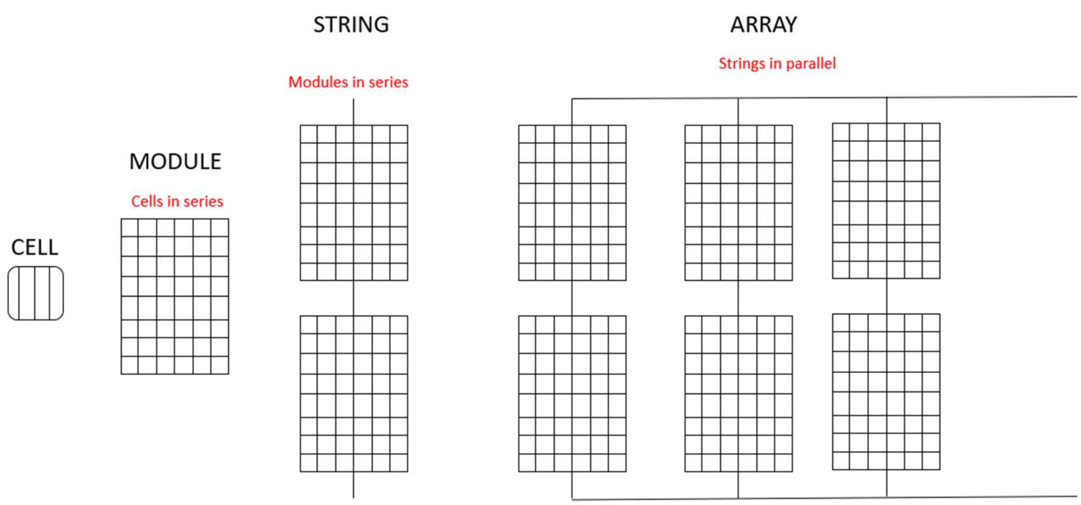


Fig 2:Solar panel array modular diagram(image courtesy of Book Solar Farms Design)

The types of PV module technology vary from solar farm to solar farm, but typically there are three types of these:

- Monocrystalline cells: produced from a single crystal, more expensive, highest efficiency.
- Polycrystalline cells: produced from many tiny crystals, less expensive, low efficiency.
- Thin-film cells: produced by applying photoactive semiconductors onto a substrate, cheap to produce, low efficiency.

Due to cost constraints and similar efficiencies, major solar farms employ polycrystalline cells in modules. The comparison between different module is as follows:

Cell Material	Module efficiency(%)	Surface area for 1 kWp (m^2)
Monocrystalline silicon	14-20	6-7
Polycrystalline silicon	13-15	6.5-8.5
Amorphous silicon thin film	6-9	11-16.5
Cadmium-telluride thin film	9-11	9-11
Copper indium gallium diselenide thin film	10-12	8.5-10

Table 1: Types of cell materials used for photovoltaic module

Inverters: they are the power electronics equipment used to convert DC power into AC power using thyristors and firing them in a particular order to generate the sinusoidal waveform. Array connects to an inverter in a solar farm; hence the number of inverters in the solar farm will as the number of arrays. The inverters used in the solar farm can be of three types:

- Micro-inverters: Every PV module has a small transformer connected to it; benefits include control of module power flow, expensive and rarely used in a solar farm. One of the famous manufacturers of micro-inverters is Enphase Energy.
- String inverters: One or more strings may be connected to an inverter, and hence there may or may not be an inverter for every array. This inverter has reasonable

control in terms of power flow and is used to some extent. Popular manufacturers are SMA.

- Central inverters: Array or sub-array is connected to a central inverter, less controllable in terms of power but are cheap and widely used in solar farms. Popular manufacturers of central inverters are Sunny Central inverters.

Inverters may or may not be equipped with a transformer; in the latter, a transformer is attached. This operation is generally used to step up the voltage at distribution voltage levels as other protective equipment is located after the transformer.

Cables or Collector Circuit: The part after the inverter-transformer combo is called the collector circuit. It is the circuit where all the power is collected from several arrays. The majority of all the protection equipment lies in the collector circuit. Collector circuits include underground cables connected to every inverter-transformer in a particular form, primarily a radial network. These cables are connected to other parts of transmission lines or cables called feeders; the role of feeders is to supply power from the collector circuit to the interconnection transformer.

Interconnection Transformer: High power equipment capable of handling power in several MVAs, typically connecting a solar farm to a utility grid. The point where the solar farm ends and the role of utility begins. Interconnection transformers can be of several sizes but are typically up to 500 MVA. Popular manufacturers of these transformers are Siemens and ABB. Generally, for studies PCC point is connected after the transformer. Several types of configuration are used in interconnection transformers like delta-wye, wye-wye, and wye-wye (buried tertiary). We will discuss in detail the last class, which is a three-winding transformer.

Three-winding transformer: Transformers having three windings involved in the core and widely used in power systems, mainly for auxiliary loads, compensation devices, or capacitor banks.

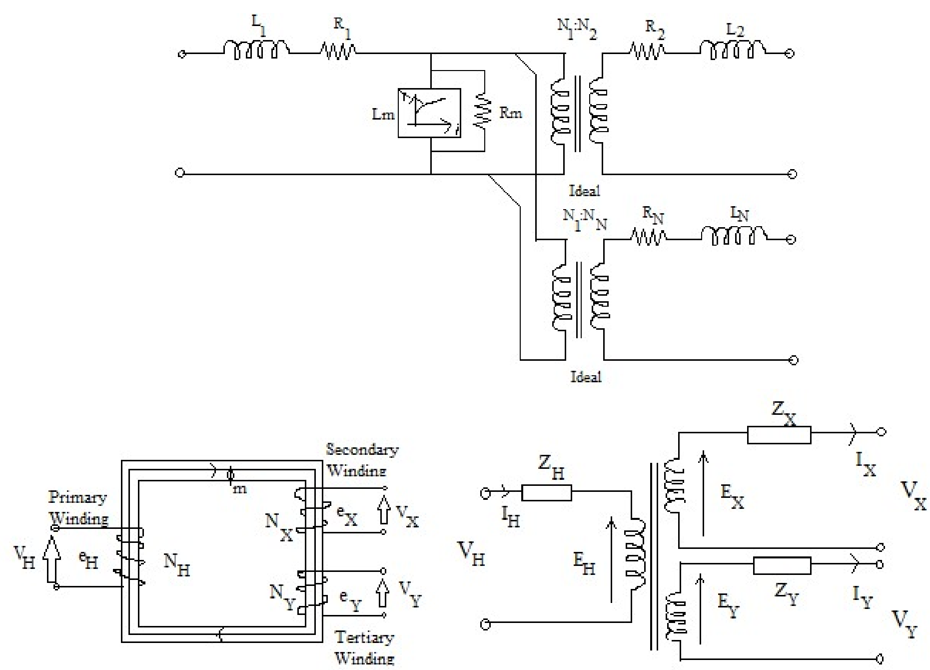


Fig 3: Winding diagram of a 3-winding transformer

The advantages offered by 3-winding transformer are [10]:

- Two secondaries are used in traction power and rectifier application.
- Harmonic compensation as using third winding decreases the impedance.
- Auxiliary supply to metering room/control room.
- Capacitor banks of different voltage ratings.

2.3 Design of generic solar farm used in the study

The solar farm used in this study is a generic solar farm and is inspired by several solar farms around the globe, which include:

- 50 MW Solar Farm, Victoria, Australia [11]
- 60 MW Solar Farm Design by Black & Veatch [12]
- Solar Star 579 MW Power Plant [13]
- 2000 MW Pavagada Solar Park, India [14]

Solar Farm/Park design: The configuration of our generic solar farm is with a capacity of 200 MW. The overall design of the generic power plant was inspired by 50 MW Solar Farm in Australia; this is mainly because the detailed design was publicly available. The design used is as follows:

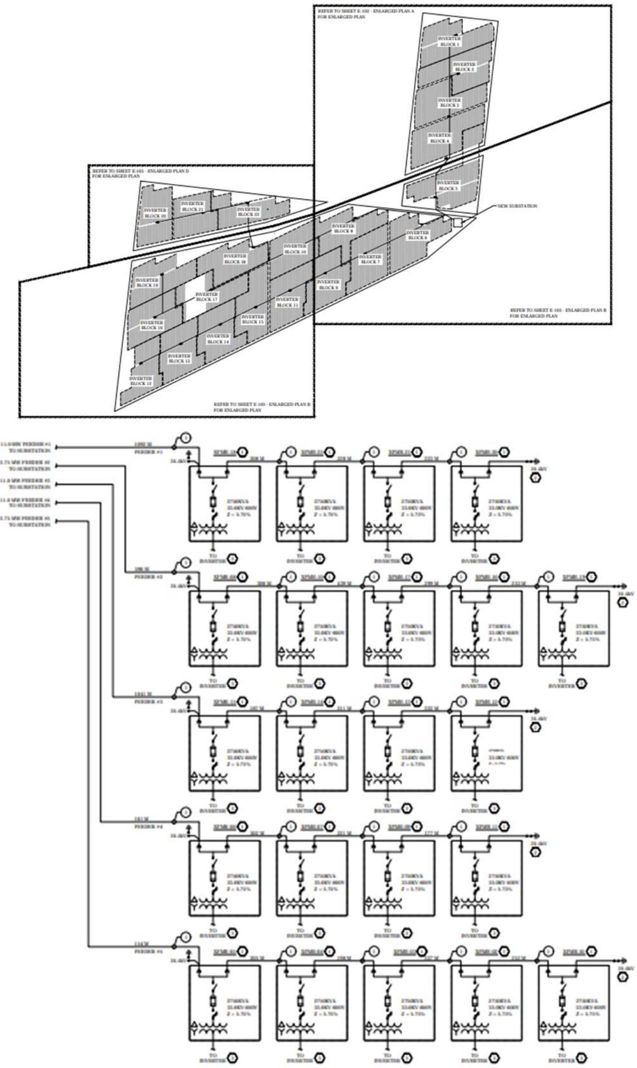


Fig 4: One-line design plan of the solar farm

Based on other parameters such as general transformer configuration used in the US and voltage levels, the modified site plan is as follows:

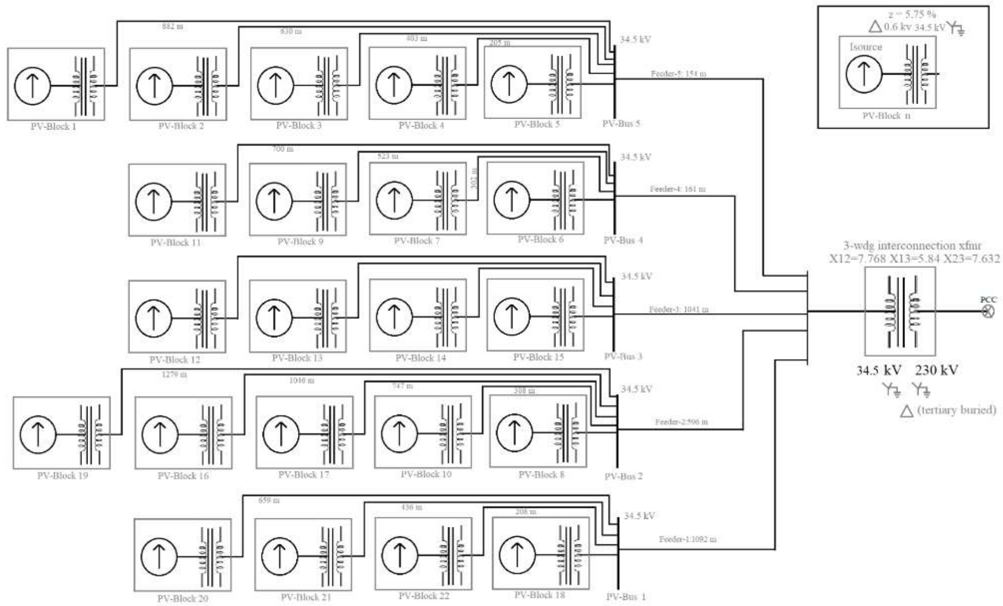


Fig 5: One-line design diagram of modeled generic plant

The diagram shown above is a single line diagram of 50 MW units in a 200 MW station. Hence such four stations were used for building up plants.

Inverters: Inverters used in the solar farm are inspired by actual inverters used in real life; inverters are designed for a capacity of 2.75 MVA, capable of providing real and reactive power. An actual inverter with similar characteristics is SMA Sunny Central Storage 2750-EV-US and TrinaPro SG3000 HV [15][16]. These inverters have similar characteristics as that of the desired inverter in a generic plant. Hence the specification of inverters is:

Input DC Voltage: 600 V
Input DC Current: 2700 Amp

Output Voltage: 600 V
Power rating: 2750 kVA
Isolation method: Transformer less
Max Efficiency: 99.0 %

Efficiency Curve:

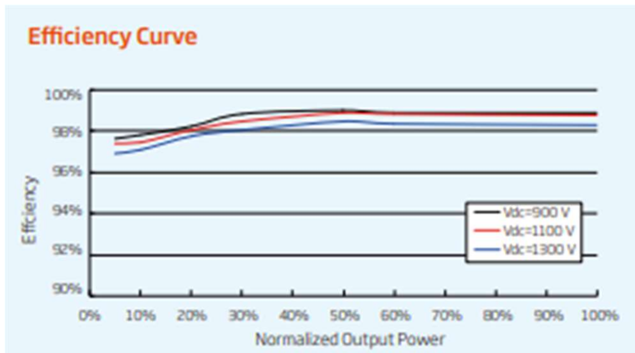


Fig 6: Inverter efficiency curve(Image courtesy of TrinaPro)

Inverter Transformer: Transformer connected to an inverter; many inverters have this inbuilt transformer. However, in this study, we assume that the inverter does not have any in-built transformer. The transformer is inspired by the Eaton Medium Voltage transformer [17] and Hitachi ABB Medium voltage dry-type transformers [18]. The specification of the generic transformer is:

Primary Voltage: 600 V
Secondary Voltage: 34.5 kV
Power rating: 3 MW
Configuration: delta-wye grounded

Cables/Collector Circuit: Cables used in solar farms are generally buried till they reach feeders, the design of cables was inspired from General Cable's Medium Voltage Industrial Cable [19], and WTEC 35 kV cable [20], similarly the design and specification of feeders were inspired from Caledonian 230/400 kV XLPE Insulated [21] and TF Kable High Voltage XLPE Cables 127/270 [22]. As seen in the circuit diagram, the collector circuit is connected in a radial network, with each inverter being at a different distance from the feeders. There are five feeders which are connected to 1 interconnection transformer.

Interconnection Transformer: this is a high-power transformer responsible for stepping up the voltage at distribution voltage levels to transmission voltage levels. The transformer was inspired by Hitachi ABB GSU [23] and Siemens Power Transformer [24]. One of the most challenging parts was finding the impedance of this power transformer; the Transformer Modelling Guide [25] was used for this purpose. The specifications of this generic transformer are:

Transformer Type: 3-winding wye-wye with a buried delta in tertiary
Primary Voltage: 34.5 kV
Secondary Voltage: 230 kV
Tertiary Voltage: 11 kV
Power Rating: 60 MVA

Capacitor: Capacitors were used for reactive power compensation as inverters cannot provide the total reactive power. Capacitors were controlled with a control mechanism that allowed them to work only when the generation of PV arrays was more than 80% of that of maximum. This assumption was used in various studies [6]. There are four capacitor units for each 50 MW generation unit connected after the interconnection transformer.

The specification of the capacitor is:

Voltage rating: 230 kV (transmission level cap bank)
Connection: Delta
Power Rating: 11.5 Mvar
Number of capacitors: 4

The simplified one-line diagram of the circuit is shown below. However, there are four MW units of 50 MW each; Figure 7 represents a one-line diagram of the combined 200 MW plant.

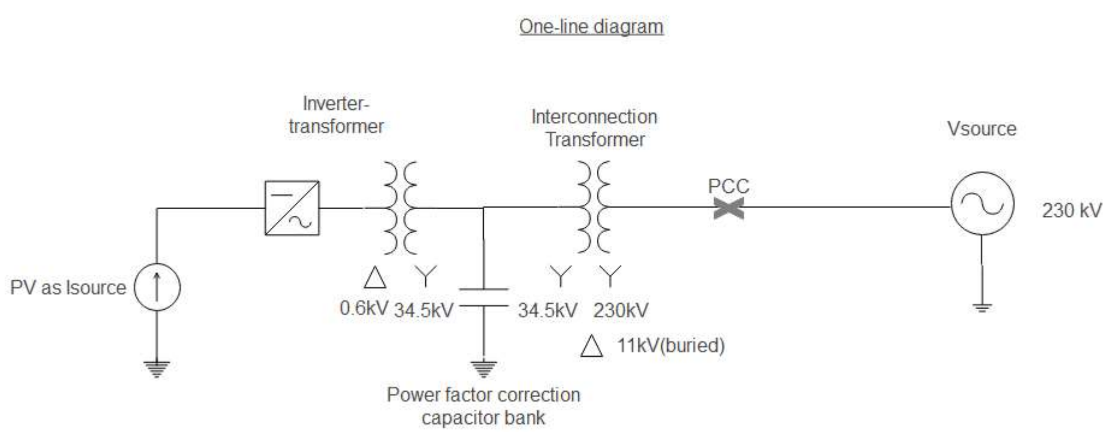


Fig 7: One-line simplified diagram of the solar farm

Chapter 3: Harmonics

Harmonics are a steady-state power quality disturbance in the system due to nonlinear loads and waveform altering devices. In this chapter, the fundamentals of harmonics are discussed, followed by standards for effective monitoring of harmonic phenomenon. The standards used for harmonic injections are IEEE 519-2014. This chapter talks about differences in different versions of the standard 519. An elaborate discussion of various harmonic measurements is done with descriptions of measurement techniques used in this study. The harmonic spectrum used in this study is mentioned at the end of this chapter.

3.1 Introduction to Harmonics

Harmonics are a type of power quality disturbance phenomenon, typically originating in end-user premises, entering the utility supply system in the form of currents with frequencies that are integral of fundamental frequency [8]. Nonlinear loads can impact the sinusoidal nature of the ac power current, hence causing the flow of harmonic current in circuits, causing interference to the operation of communication network circuits and other equipment. This flow of harmonic current can cause additional heating losses in electromagnetic devices, causing resonance conditions in capacitors employed in power factor correction, resulting in an increased level of harmonic voltage and currents [26][27]. Harmonics are mainly generated by devices that have nonlinear voltage-current characteristics. The primary sources of harmonics in industrial systems can be from sources listed below:

- Static power converters- rectifiers, inverters, etc.
- Saturated magnetic devices
- Arc furnaces

As major components used in industrial and commercial systems employ such nonlinear devices, the need to perform harmonic study arises as it can become significant design consideration in planning studies due to problems such as resonance and interference [28].

A capacitor generally connects distribution/transmission networks for power factor improvement and voltage regulation. Due to overhead lines been inductive can cause interaction of capacitor resulting in resonance conditions. These frequencies can be discovered using frequency scans as the resonant frequencies will have peaks in impedance scans [29][30].

3.2 Harmonic Standards-IEEE 519

Implementers of IEEE Standards documents are responsible for determining and complying with all appropriate safety, security, environmental, health, and interference protection practices and all applicable laws and regulations. Standards are documents purposed for providing specifications and procedures so that systems can operate safely without damage to any person, object, or service.

Standards are defined to address protocols to maximize product compatibility, public health, and customer safety. They help formulate fundamental building blocks for practices and product development. They ensure that the practices and procedures are widely understood, allowing incompatibility, interconnectivity, and product development [31].

IEEE-519 are the standards used for setting limits on voltage and current distortion. These standards define design criteria for current and voltage harmonics for an electrical system, assumed to have linear and nonlinear loads. The standards are updated with industry development, introduced in 1981. They have been revised several times [32].

3.3 General terms related to IEEE 519

The point of common coupling is the closest point to the electric utility where single or multiple customers are present concerning distribution supply systems [33]. PCC is the point about which all analysis must be performed regarding IEEE 519, and every measurement or data collection in this work is performed about PCC. It is also called a point on a public power supply system, electrically closest to a specific load. The PCC is a point located upstream of the regarded installation [2]. Below is the pictorial depiction of PCC:

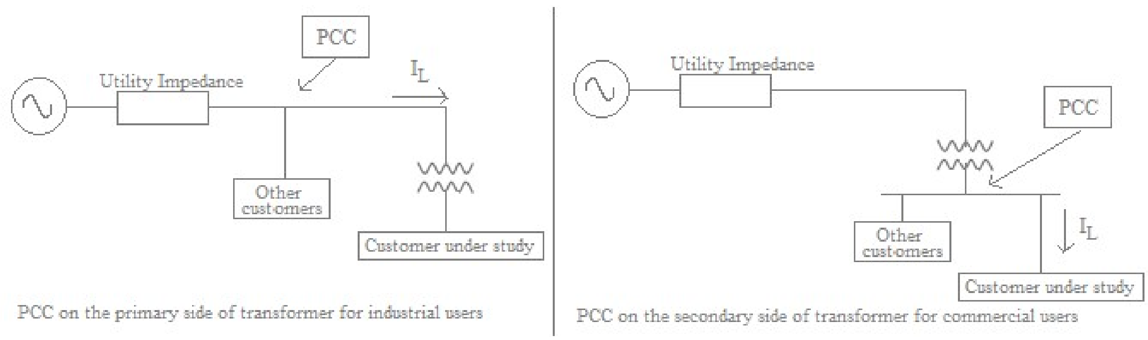


Fig 8: PCC depiction on most widely used cases [Image courtesy of Power Quality Solutions and Meters]

I_{SC}/I_L ratio is the ratio of short circuit current capacity to the value of load current at the point of common coupling. IEEE 519 defines I_{SC} as the maximum short-circuit current at PCC and I_L as the maximum demand load current at PCC. The I_L, however, does not mean instantaneous peak in current; it just simply means current from the maximum demand billing. The term I_{SC}/I_L is also called Short Circuit Ratio or SCR, typically used in power quality analysis. SCR is an accurate measure of the type of bus; a bus with high SCR is referred to as a strong bus, whereas a bus with low SCR is referred to as a weak bus. Standards are meant for various short circuit current rating scenarios; hence, different harmonic limits are used for multiple short circuit capacity categories [34].

Total Harmonic Distortions or THD is defined as the root-mean-square value(RMS) of the waveform harmonic components as a percentage of the RMS value of the fundamental waveform. It is used in low-voltage, medium-voltage, and high-voltage systems. It can be expressed as:

$$THD = \sqrt{\frac{sum\ of\ all\ squares\ of\ amplitude\ of\ all\ harmonic\ voltages}{square\ of\ the\ amplitude\ of\ the\ fundamental\ voltage}} \times 100\% \quad (1)$$

$$THD = \frac{\sqrt{\sum_{h=2}^{50} V_h^2}}{V_1} \times 100\% \quad (2)$$

Total Demand Distortions or TDD is defined as the root-mean-square value of harmonic current distortions in % of the maximum demand load current.

$$TDD_I = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + I_5^2 + \cdots}}{I_L} \quad (3)$$

THD and TDD are very similar terms**;** THD calculates distortion in voltage to fundamental quantity whereas. In contrast, TDD calculates distortion in current to maximum loading conditions. The difference between THD and TDD is essential because if THD_i would be used for current distortions, a user may be penalized unfairly for harmonics during light loading conditions. During light loading, it may seem that harmonic current contribution in % has increased even though the actual harmonic currents in amperes have remained the same or decreased [32].

Several terms are needed to be discussed regarding IEEE 519-2014, which were not present in the 1992 version. Differences between the two versions are discussed first, followed by elaboration on the 2014 version.

3.4 Differences between 1992 version and 2014 version

New changes made in new standards require harmonic analysis to include the stochastic nature of distortions. These changes are mainly different from the 1992 version because the previous one expected the harmonic analysis for steady-state or static nature. However, this new standards analysis must be performed over a period, which gives adequate data for considering percentiles. Percentiles enable the removal of outliers and data corresponding to occasional events. The 1992 version provided for an in-depth definition of various terms like THD, TDD, and PCC. Hence in that respect, the 2014 version can be considered a modification of the 1992 version with stochastic nature and percentile-based analysis.

3.5 Harmonic measurement terms defined in 2014 version

The specified measurement window width used by digital power quality meters is 12 cycles or 200 milliseconds; the cycle just refers to the power system's frequency in the US. Hence each point for consideration must be tabulated using the 12 cycles period. The next measurement term is very short time measurements; they are simply an aggregation of the 15 such points (where 1 point is a measurement over 12 cycles) for a 3-sec interval. The formula used for computation of 1 VSTM is:

$$F_{n,vs} = \sqrt{\frac{1}{15}\sum_{i=1}^{15} F_{n,i}^{2}} \tag{4}$$

The next measurement quantity is short time measurements; they aggregate 200 very short time measurements tabulated over a 10-period interval. The formula used for calculating STMs is:

$$F_{n,sh} = \sqrt{\frac{1}{200}\sum_{i=1}^{200} F_{(n,vs),i}^{2}} \tag{5}$$

For the sake of simplification:

1 point: 200 milliseconds / 12 cycles

1 VSTM (very short time measurement): 15 points = 15 x 200 milliseconds = 3000 milliseconds or 3 second; 1 STM (short time measurement): 200 VSTMs = 200 x 3 seconds = 600 seconds or 10 minutes

3.6 Harmonic measurements used in this study

The main challenges in performing such a study are the availability of data of such small order. If we were to perform the study, we would require datasets of each point been 200 milliseconds away, which is difficult to find. Hence for the sake of simplification, we will only be considering Short time measurements due to data in a range of seconds and the dataset used in the study (explained in section 4.5). Dataset used is based on a 1-minute interval, which means 10 points for calculation of 1 STM. The formula is modified as:

$$F_{n,sh} = \sqrt{\frac{1}{10}\sum_{i=1}^{10} F_{(n,vs),i}^{2}} \tag{6}$$

Here 1 point refers to a 1-second interval, and hence the values corresponding to 1 VSTM cannot be performed in this study. However, there are some publicly available datasets having a measurement window of 1-seconds. Using them in this study would be very difficult, as performing each week's simulation would require a time frame of several days, if not a week. Hence, performing for several weeks with the difficulty of achieving the debugging task would take a long time. Analyzing with 1 minute provides us with reasonable accuracy as a realistic system and can be used for the pre-performed analysis of harmonic distortions.

3.7 Percentiles and their calculation

Percentile, in statistics, is defined as the score below which a certain percentage of data will lie in frequency distribution [35]. The steps used for calculating for any percentile "k" are:

- Arranging data values in increasing order.
- Multiplying the required percentile number by dataset length. This value will generate the index. We will handle values based on the index, e.g., first, second, etc.
- We are rounding up the index if required to the nearest whole number.
- Using the ranked data for finding percentile based on index [36].

For example, let us take a day into account; we will have 1440 minutes for calculation for one day. Hence the steps for finding the percentile of letting us assume 90th will be as follows:

- Ranking the 1440 points in ascending order
- Multiplying 90% by n (=1440) = 0.9 x 1440 = 1296
- An index is a whole number; hence we got to step 4.
- Values greater than or equal to the 1296th position is our percentile.

A similar methodology is used throughout this study for finding percentiles.

3.8 IEEE 519-2014 version- limits regarding voltage and current

Voltage limits:

At the point of common coupling, system operators and owners shall limit voltage harmonics as follows:

- Daily 99th percentile VSTM (3 s) should be less than 1.5 times the values given in table 2.
- Weekly 95th percentile STM (10 min) should be less than the values given in table 2.

Bus voltage V at PCC	Individual harmonics(%)	Total harmonic distortion THD(%)
$V \leq 1.0$ kV	5.0	8.0
1 kV < $V \leq 69$ kV	3.0	5.0
69 kV < $V \leq 161$ kV	1.5	2.5
161 kV < V	1.0	1.5[a]

Table 2: Voltage distortion limits according to IEEE 519-2014

Current limits:

The current distortion limits are specified for various voltage levels where the analysis will take place. However, the percentile value requirements for every voltage level is exact which is:

- Daily 99th percentile VSTM (3 s) harmonic current values should be less than 2.0 times the values given in table 3.
- Weekly 99th percentile STM (10 min) harmonic current values should be less than 1.5 times the values given in table 3.
- Weekly 95th percentile STM (10 min) harmonic current values should be less than the values given in table 3.

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order(odd harmonics)[a,b]						
I_{SC}/I_L	$3 \leq h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h < 50$	TDD
<20	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Table 3: Current distortion limits for voltage in between 120 V and 69 kV

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order(odd harmonics)[a,b]						
I_{SC}/I_L	$3 \leq h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h < 50$	TDD
<20	2.0	1.0	0.75	0.3	0.15	2.5
20<50	3.5	1.75	1.25	0.5	0.25	4.0
50<100	5.0	2.25	2.0	0.75	0.35	6.0
100<1000	6.0	2.75	2.5	1.0	0.5	7.5
>1000	7.5	3.5	3.0	1.25	0.7	10.0

Table 4: Current distortion limits for voltage in between 69 kV and 161 kV

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order(odd harmonics)[a,b]						
I_{SC}/I_L	$3 \leq h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h < 50$	TDD
<25	1.0	0.5	0.38	0.15	0.1	1.5
25<50	2.0	1.0	0.75	0.3	0.15	2.5
>50	3.0	1.5	1.15	0.45	0.22	3.75

Table 5: Current distortion limits for a voltage greater than 161 kV

Even harmonics are limited to 25% of the odd harmonic limits above
Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed
All power generation equipment is limited to these values of current distortions, regardless of actual I_{SC}/I_L
Where:
I = maximum short-circuit current at PCC
I_L^{SC} = maximum demand load current(fundamental frequency component) at PCC under normal load operating conditions

3.9 Inverter Harmonic Contribution

Inverters are a significant contributor of harmonic current in a solar farm, as inverters are connected to PV arrays which generate DC. Converting to AC requires the use of inverters, which also generate non-sinusoidal components [37]. Other types of equipment used in a solar farm are protection devices or power conversion elements; hence the harmonic contribution is minimal. Every PV array is located at a different distance from the interconnection transformer, will have different lengths of cables and, therefore, different impedance values. As harmonic current and voltages may vary by impedances, every panel will generate a different harmonic current, which adds up at the interconnection transformer. Hence as inverters are the major contributor of harmonic current, the study only focuses on using inverter spectrums, and no spectrum will be assigned for other components.

Inverter Spectrum: Harmonic spectrum contains the contribution of each harmonic number. Using an accurate harmonic spectrum is necessary for this study because an inaccurate harmonic spectrum may lead to incorrect current contribution. As the inverters used in this study are high power inverters having power in the order of few MVAs, the manufacturers of such inverters are not significant in number. As this spectrum is generally a part of the testing of an inverter in the lab, the results of such a large-scale MVA inverter are not publicly available. The only available test results are inverters with low power provided by the NICE lab [38] and a few others with small power ratings. The publicly available spectrum looks like as shown below:

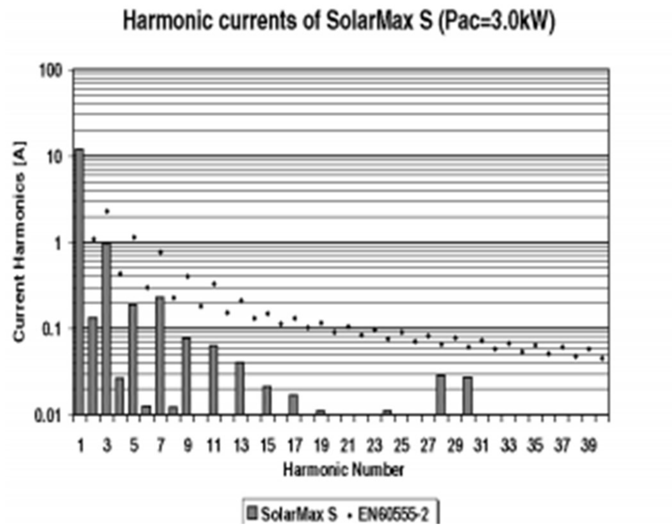


Fig 9: Inverter harmonic spectrum for SolarMax S

Hence to perform this study, the harmonic spectrum used in [20] was used; the analysis performed in [20] has access to industry data for high power inverters, and this study uses that. The harmonic spectrum use is as follows:

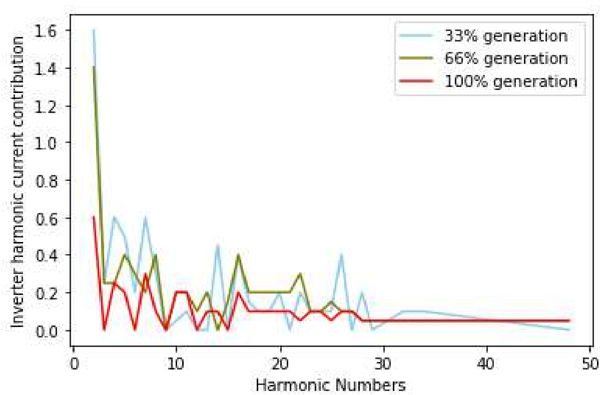


Fig 10: Inverter spectrum for modeled inverter

Chapter 4: Modelling and Simulations

Modeling is an essential aspect of this study. In this chapter, modeling software like OpenDSS and Python are discussed, followed by solar irradiation data, and this data is one of the most critical parts of the solar farms. The following important part of the chapter is modeling inverters and their methodology, followed by a discussion on the solar farm model and the actual model's attachment. Essential aspects such as simulation environment are discussed later in this chapter, followed by validation of interconnection transformer.

4.1 Modelling software/tools description

The software and tools used in this study were to investigate the harmonic impact caused by a solar farm, and the study tries to reciprocate the real-life scenarios with the actual solar farm. The tools used by this study are:

OpenDSS- OpenDSS stands for open-sourced distribution systems simulator, is a line-based power system simulation tool used in modeling and analyzing distribution circuits. Primary functionalities of OpenDSS include steady-state analysis of distribution circuit with features such DER integration, voltage control devices, and ability to communicate with other software such as python/MATLAB. OpenDSS is used since 1997 and was released by Electric Power Research Institute. Typical use of software includes analysis of

DER resources connected to utility systems, harmonic analysis, and energy efficiency [39]. Though a significant part of OpenDSS is for distribution systems, designing the transmission systems with more user-defined parameters can be used. Also, OpenDSS is open-source software; there are plenty of external tools which can be used to simulate conditions that OpenDSS may not be able to perform. OpenDSS has a feature called a discussion forum, where numerous people from around the globe share their opinions on new ideas and modeling techniques.

OpenDSS was used to build a solar farm model; all the electrical apparatus used to simulate a generic solar farm was fully modeled in OpenDSS. OpenDSS is good at performing fault analysis, DER penetration studies. However, OpenDSS can only conduct a harmonic study in static nature, only for a single snapshot of a particular time. Hence we need external tools to simulate the study as the requirements of IEEE 519-2014 mentions weekly analysis, which is technically called quasi-static time series simulation and cannot be performed individually in OpenDSS. We would require external tools like Python or MATLAB to drive OpenDSS this QSTS.

Python- Python is a high-level, general-purpose programming language, employing code readability and an object-oriented approach, which helps coders write straightforward programs [40]. For developing the simulation environment, Python on its own may prove difficult with little scope for data visualization. Hence Spyder was used for creating a python script. Spyder is an open-source scientific environment written in Python. Researchers and engineers mainly use it for data analysis. Its functionalities include easy readability and analysis of code with features such as data visualization and various scientific packages [41].

Spyder/Python script was used to drive the OpenDSS model. Hence the external communication was performed in Python with crucial aspects such as statistical analysis.

Communication of OpenDSS/Python script: as OpenDSS and Python are two complete tools created by different professionals, the creators of OpenDSS have taken this into account. Many people may use OpenDSS only modeling and drive simulations through something else. Creators of OpenDSS has created numerous communication interface which can use by investigators who want the best of two worlds. Numerous guides and documents are created by EPRI (creators of OpenDSS) [42][43][44][45]. All the documents were used for building the simulation environment for this study. The communication interface is called OpenDSS COM, and the use for the same will be described later.

4.2 Solar Irradiation

Solar irradiance, defined as power per unit area received from the Sun as electromagnetic radiation, measured in watt per square meter (W/m^2) [46]. Photovoltaic solar farm work on solar irradiation is a significant part of this study to determine irradiation profile, which will help us understand the harmonic current injection better. There are days which will be referred to often; here is the meaning of those:

- Clear day: A day when the irradiation profile is perfect with high irradiance.
- Cloudy day: A day when the irradiation profile is with clouds, with irradiance like a clear day
- Very cloudy day: A day when there are many clouds, with lower irradiance than a clear day.

For simulations, these days were used in combination to have better visibility of the system. Hence for this purpose, the following type of profiles was selected to be simulated:

- Clear Week: Containing all clear days.
- Cloudy Week: Containing all cloudy days.
- Very Cloudy Week: Containing all very cloudy days

The purpose of selecting a clear week is to observe the high current injection by inverters. Similarly, there will be irradiance with cloud cover in the cloudy week, impacting the current injections. There will be reduced irradiance with cloud cover for very cloudy, which is expected to have more reduced current injections.

4.2.1 Terms related to solar irradiation

Solar irradiation is a diverse topic, and here are few terms defined by [47] which are fundamental for understanding solar irradiation measurement:

- Direct Normal Irradiance (DNI) is defined as the amount of solar irradiation received per unit area by a surface held perpendicular to the rays coming in a straight line from the Sun's direction at its instantaneous position in the sky. DNI can be maximized by aligning the surface normal to incoming irradiation.
- Diffuse Horizontal Irradiance (DHI) is defined as radiation received per unit area by a surface that does not follow a direct path from the, scattered by molecules and particles in the atmosphere, and comes equally from all directions.
- Global Horizontal Irradiance (GHI) is defined as the total amount of shortwave radiation from above by a surface horizontal to the ground. This quantity summarizes direct and diffused irradiation coming from the Sun or summation of DNI and DHI.

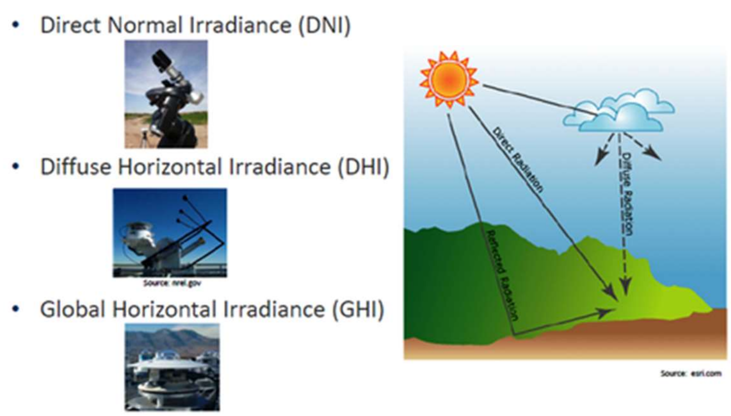


Fig 11:Three types of radiation(Image courtesy of esri.com)

4.3 Dataset

4.3.1 Source of Dataset

Datasets containing the solar irradiation profile were used from National Renewable Energy Laboratory's Solar Radiation Research Laboratory. The facility located in Golden, CO, has good solar radiation penetration and an excellent view of the horizon.

Researchers in this facility use various devices like pyranometers and photometers to collect solar radiation data for various research activities. Data collected by this facility is available publicly and can be used by researchers for multiple projects [48].

The data used in this study is publicly available at NREL's Measurement and Instrumentation Data Center [49].

Fig 12:NREL MIDC (Image courtesy of NREL.gov)

The picture above is the location of the instrument where the measurements were taken, and the instrument used to measure the solar irradiation is a pyranometer shown below [50]:

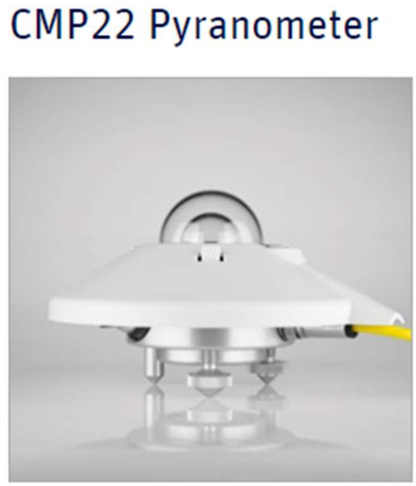


Fig 13: Image of a typical pyranometer

The location is critical where the measurements were taken, the location of the instrument as follows:

Latitude: 39.7420 North
Longitude: 105.180 West
Elevation: 1828.8 meters AMSL

4.3.2 Information of the dataset

The dataset is 1-year data with a resolution of 1-min; the specifics of the dataset are:

Data range: Jan 1st, 2019 to Dec 31st, 2019
Data resolution: 1-min
Type: CMP22(vent/corr)

The instrument used for measurement: CMP22-Total Hemispheric shortwave irradiance measured by a Kipp & Zonen pyranometer with calibration factor traceable to the World

Radiometer Reference (WRR). As the profiles desired for this study were chosen from the entire yearly data, the annual data is shown in Fig 14.

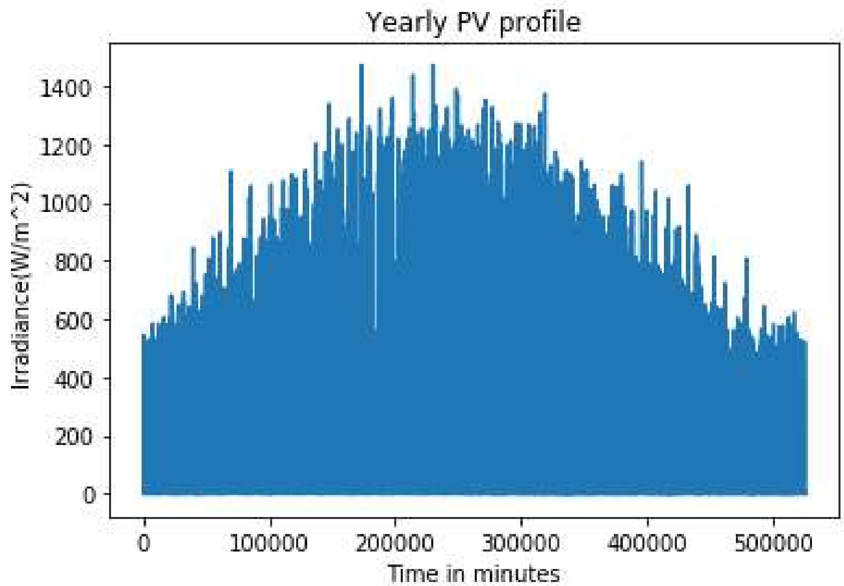


Fig 14: Yearly solar irradiation data used in the analysis

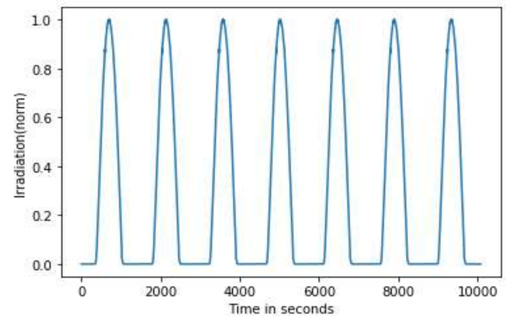
The number of Datapoints in 1-day: 1440

Datapoints in 1-year: 1440 x 365 = 525600

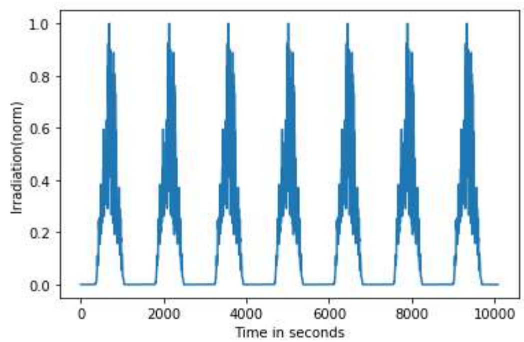
It is observed that irradiation reaches its high around the middle of the year, around summer. The irradiation reaches its low in the winter period, which is around December-January. Based on careful analysis of the data, three different irradiation profiles were selected, and 3-week synthetic data was created for research. Synthetic data intended to form precise results from a type of profile.

The weekly period selected for the study are:

Clear Week:



Cloudy Week:



Very Cloudy Week:

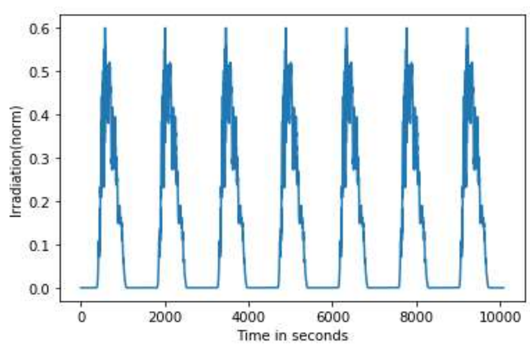


Fig 15: Irradiation profiles for a clear, cloudy, and very cloudy week

4.4 Modelling of Inverters

An essential aspect of modeling a solar farm is how a PV module should be modeled. As per the design of the solar farm, every array has a central type of inverter connected to one array; one of the features of OpenDSS is that it inherently models an inverter with a PV system cell. Hence for this study, every PV module represents a PV array in a real-life solar farm. How a PV array can be modeled in OpenDSS are:

- PVsystem
- Load with negative kW
- Generator Object
- Isource Object

The above ways are the possible ways in which a solar array can be modeled; every way will behave as the modeled PV array in almost all the solution modes in OpenDSS.

However, during the harmonic solution, the possible outcomes are converted into:

- PVsystem becomes Vsource.
- The load becomes Isource.
- Generator becomes Vsource.
- Isource remains Isource.

Two of the ways above get converted into Vsource, and two others become or remain as Isource. Generally, it is preferable to model the PV array as Isource because it helps during analysis perform in resonance.

4.5 Methodology for interpolation algorithm:

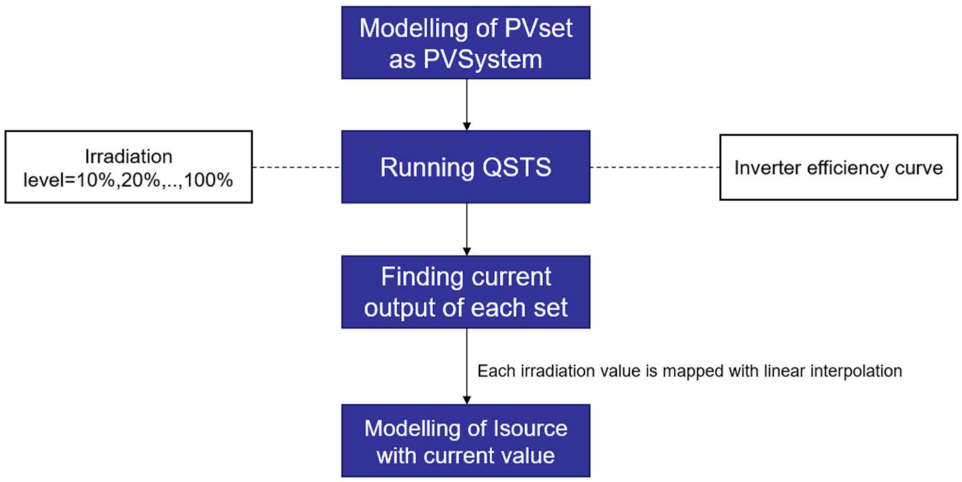


Fig 16: Flowchart for interpolation algorithm

The interpolation algorithm for finding current for desired irradiation level is found using the above diagram. The process starts with modeling the PV array as PVsystem, then assigning the irradiation level 10% with inputs of inverter efficiency. Each array calculates the current; this current is used in interpolation for 10 % irradiation level. The irradiation is increased by 10%, and the algorithm carries a similar step. At the end of the entire process, we have irradiation levels and the corresponding current, which each PV array will inject.

After implementing the above techniques, the solar farm was modeled.

4.6 Solar farm model

The one-line diagram of the model is as shown below:

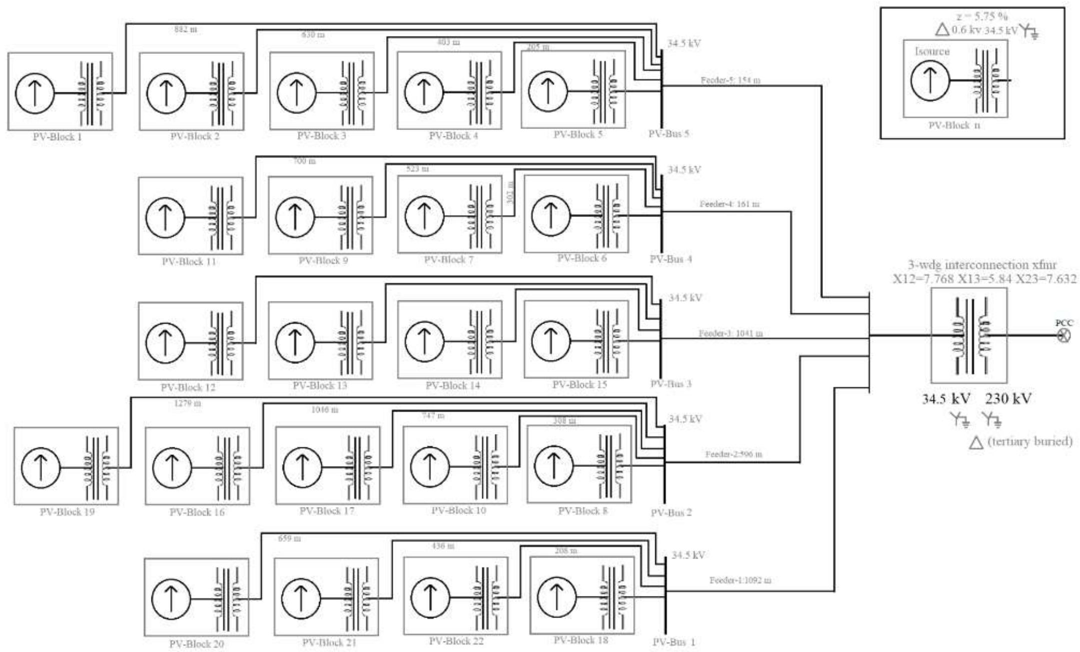


Fig 17: One-line diagram of a 50-MW unit

The master file means the file which will call all the components which may have been defined separately; the master file model looks like this:

```
Clear
new circuit.SolarFarm
~ basekv=230 pu=1.0001 phases=3 bus1=SourceBus
~ Angle=30
~ MVAsc3=2000 MVASC1=2100
Redirect Group1.dss
Redirect Group2.dss
Redirect Group3.dss
!Redirect Group4.dss
Redirect Inverters.dss
Redirect MainXmissionLine.dss
```

```
Redirect Capacitors.dss
Redirect Monitors.dss
Set Voltagebases=[230,34.5,11,0.6]
Calcv
Solve
!Solve
!show mon HarmonicCurrentPCC
The redirection to groups is because the 200 MW Solar farm is modeled
as 4 x 50 MW individual solar farm, each group look as below:
Redirect cables_xmission_lines.dss
Redirect Interconnection_xfmr_1.dss
Redirect Feeders_1.dss
Redirect Collector_circuit_1.dss
Redirect Inverter_Xfmr_1.dss
!Redirect Inverters_1.dss
```

Now, we will dive deep into each component employed in a solar farm; the modeling of the inverter was done as

```
New Spectrum.current_spectrum NumHarm=32 CSVFile=Spectrum.csv
New Isource.PV_Inv_1 bus1=Inv_1 phases=3 amps=2646.19
spectrum=current_spectrum
New Isource.PV_Inv_2 bus1=Inv_2 phases=3 amps=2646.19
spectrum=current_spectrum
New Isource.PV_Inv_3 bus1=Inv_3 phases=3 amps=2646.19
spectrum=current_spectrum
All the way till…
New Isource.PV_Inv_65 bus1=Inv_65 phases=3 amps=2646.19
spectrum=current_spectrum
New Isource.PV_Inv_66 bus1=Inv_66 phases=3 amps=2646.19
spectrum=current_spectrum
```

The transmission line was modeled as:

```
New Line.HV_transmission_1 Bus1=Sourcebus
Bus2=Solar_Plant_Interconnection
~ Geometry= Xmission
~ Length= 1 units=km
New Line.HV_transmission_2 Bus1=PCC Bus2=Solar_Plant_Interconnection
~ Geometry= Xmission
~ Length= 0.5 units=km
```

The capacitor bank was modeled as:

```
New Capacitor.Cap_1 Bus1=Solar_Plant_Interconnection Phases=3
Kvar=11500 Kv=230 Conn=delta
New Capacitor.Cap_2 Bus1=Solar_Plant_Interconnection Phases=3
Kvar=11500 Kv=230 Conn=delta
New Capacitor.Cap_3 Bus1=Solar_Plant_Interconnection Phases=3
Kvar=11500 Kv=230 Conn=delta
New Capacitor.Cap_4 Bus1=Solar_Plant_Interconnection Phases=3
Kvar=11500 Kv=230 Conn=delta
New CapControl.C1Cntrl element=Line.HV_transmission_2 Capacitor=Cap1
Type=Current ON=400 OFF=380 Delay=10
```

The Monitor used for calculation of harmonic voltage and current contribution at PCC is modeled as:

```
! Monitor for measuring for various quantities
New Monitor.HarmonicCurrentPCC element=Line.HV_transmission_2 mode=0
term=1 ppolar=no
```

4.7 Simulation environment/quasi-static time-series Simulation

The study is conducted with the combination of OpenDSS and Python; the entire process is described as:

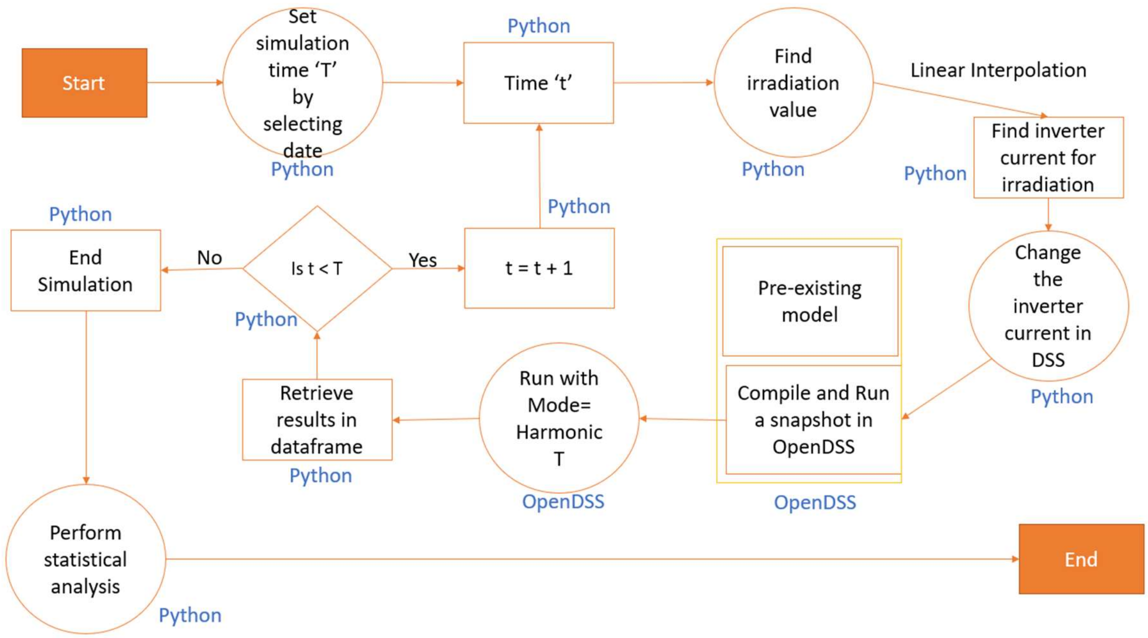


Fig 18: Flowchart for simulation set-up

The stepwise breakdown of the entire simulation set-up is described as follows:

Start: The start of the simulations

Set simulation time ‘T’: setting the time for which the simulations are performed by selecting the date range, for example, the study is to be conducted for dates of 15 January to 22 January, then we will provide the date range, and the code will set the simulation time as the difference between two dates, i.e., one week for the example above.

Time 't': Instantaneous time, which is to be analyzed, will start at zero and end at the end of simulation time 'T'; this time will keep incrementing by one step after performing the static analysis of the model.

Find irradiation value: This step involves finding the irradiation value at the specified time 't' and using it for retrieving the irradiance value. For instance, if the simulation is performed for 1-week with dates 15 January to 22 January and the time 't' is 720, which means noon on 15 January, hence the irradiation value at the time maybe 800 W/m^2 will be used for analysis.

Find inverter current for irradiation: This step involves finding the inverter currents as the solar modules are modeled as current sources. The first step is finding the full load inverter current when the inverter provides 100 % rated power. Then this current is used while modeling the inverter's model. Then during the QSTS, the instantaneous irradiation is used for finding the instantaneous inverter current by linear interpolation using the maximum inverter current. The finding of harmonic spectrum is also executed in this step as the inverter spectrum varies with power generation; this spectrum is also calculated with the instantaneous solar irradiation and provided inverter spectrum as discussed earlier.

Change the inverter current in DSS: This step involves changing the inverter current calculated in the previous step and assigning the new current to the OpenDSS model. This step is performed in Python and requires communication between Python and OpenDSS via OpenDSSCom. The desired value is communicated to OpenDSS, and it results in assigning the desired current to the inverter modeled as current sources.

Compile and Run the new model in OpenDSS: This step involves running the new model with the new assigned inverter current in OpenDSS, ensuring that model is working. Though this step is performed in Python, the compiling takes place in OpenDSS.

Run with mode=HarmonicT: This step involves running the model in a mode called HarmonicT. HarmonicT is a type of solution that can be performed in OpenDSS like daily, yearly, or fault study. In this mode, all power delivery elements are assigned a harmonic profile. As there are no other harmonic-producing components in the circuit, we only set the profiles to current sources. OpenDSS will perform the harmonic analysis of the model for the specified time step. As we are using the T abbreviation, OpenDSS will save the value when they can be helpful in the solution for the next timestep.

Retrieve results in a data frame: After OpenDSS has performed the harmonic analysis, the solutions are exported by OpenDSS as monitors; these monitors are exported as CSV files by the DSS. Python then performs the task of reading the CSV file and saving the results in the desired format.

Is $t < T$: This step is a decision step, as the time 't' will be incremented after each 't' analysis is performed by the Python-OpenDSS combo, if the time 't' was the last time step, then the simulation set-up will proceed to "End Simulation" command, however, if the 't' is less than ‘T,’ then the value of ‘t’ will be incremented by one and the simulation will perform the above tasks again. This step is equivalent to a loop like for or while loops.

Perform statistical analysis: After the looping phase is completed and the harmonic analysis part is performed, the next step is statistical analysis. In this step, the results for the entire time frame are analyzed, and various data visualization techniques are performed to understand the data better. The analysis can formulate a conclusion about the nature of the harmonic current injected by the solar farm.

End: This step involves the end of simulation and analysis.

Using the methodology explained above, the code for the simulation environment was constructed and is herein presented:

Pseudo-code-simulation environment

The role of simulation environment is to communicate with OpenDSS model and perform statistical analysis. Below is an example of how code for communication between Python and OpenDSS looks,

```
for i in range(simulation_time_steps):
    current_value_from_irradiation(irradiation)
    harmonic_contribution_from_current(current)
    sourceName = “Name_of_Inverter”
    dssCircuit.setActiveElement(sourceName)
    dssElem.Properties('amps').Val = desired_current_value
    dssSolution.Solve()
```

The code above is a pseudo code for the sake of explanation, the breakdown for which is:

- Line 1: Finding current injected by inverter based on irradiation
- Line 2: Finding harmonic contribution based on current and irradiation
- Line 3 through 5: Communication set-up with OpenDSS where Active element defines the element we are changing, and properties change the quantity desired
- Line 6: Solves the frequency domain solution

Detailed code is attached in the appendix; readers can look if they want to understand the process better.

4.8 Interconnection transformer validation

The interconnection transformer that connects the solar farm to the primary transmission circuit is a three-phase three-winding configuration. However, for this study, the parameters considered for modeling the transformer are reasonably accurate. Finding the data for such a high-power transformer is a difficult task. However, some datasheets and reports can be used to estimate the value of the impedance of the transformer. One of such datasheets is a datasheet by GE-Prolec Transformer [51]. The datasheet is also shown below:


PROLEC
Powering reliable solutions for you

Step Up 3 Windings Transformer for Windfarm Applications

Prolec GE has developed a 3 winding transformer for wind turbines with a doubly fed induction generator technology, which requires a third winding to feed the rotor generator.

Product characteristics includes... step up application with an electrostatic shield for a protection against new electronic technology applied in new generation wind turbines.

Product scope / standard features

- 3400 kVA total rating
- High voltage 34.5 kV (to the collector system)
- Medium voltage 6 kV (input from the generator)
- Low voltage 690 V (tertiary winding to feed rotor generator)
- ONAN
- 60 hertz
- 65°C temperature rise
- Altitude up to 3300 FASL
- HV tap charger
- Loop feed dead front HV terminals
- Impedances:
  - LV to MV 3.6 to 6.6 %
  - MV to HV 6.0 to 7.3%
  - LV to HV 9.9 to 14.3 %
- Finish color Green Munsell 7GY 3.29/1.5
- Built to all applicable IEEE standards

Special features

- 55°C temperature rise
- Bayonet fuse holders with flappers
- High fire point fluids
  - silicone
  - hydrocarbon
  - vegetable fluids
- Internal oil switch (radial or loop)
- Under oil internal arresters
- Seismic designs IBC Certified
- Stainless steel tank and cabinet construction
- Optional colors
- Full 200 kV BIL in windings and accessories

Value Added

Concept	Features	Value point
Step Up	Increased margin for transformer over excitation	Prevent core saturation, partial discharges, and gassing
Electronic Protection	* Electrostatic Shield	Provide a pathway to ground for any residual resonance
Network Protection		Prevent capacitive coupling between the grid and capacitive banks of the inverter
Tertiary winding	Third winding to feed the induction rotor generator	Reducing the number of components to be installed up in the nacelle

Standards and certifications available

LISTED
c LISTED
SEISMIC CERTIFIED
FM APPROVED

Fig 19: Specification sheet for a 3-winding transformer

However, using this datasheet is that the power ratings are low compared to the synthetic transformer used in this study. Similar kind of data are available from various manufactures; all the datasheets were used for motivation of the designing the transformer, which are:

- GE-Prolec [51]
- Siemens Energy [53]
- ABB [54]

Other studies [52] were also used for the estimation of parameters. Based on these various data sources, the impedance value selected for the transformer are:

X12 = 7.768 %
X13 = 5.84 %
X23 = 7.632 %

Where Xab means impedance between winding 'a' and 'b.'

The modeling of such a three-winding transformer can be reasonably performed in OpenDSS; however, for determining whether the modeled transformer behaves as per our expectation, we need to carry out validation tasks for such modeled transformer. The description of the task can be found as follows:

For performing validation of the modeled transformer, a short circuit test was performed. A short circuit test aims to determine the series branch impedance of a transformer parameter in the equivalent circuit.

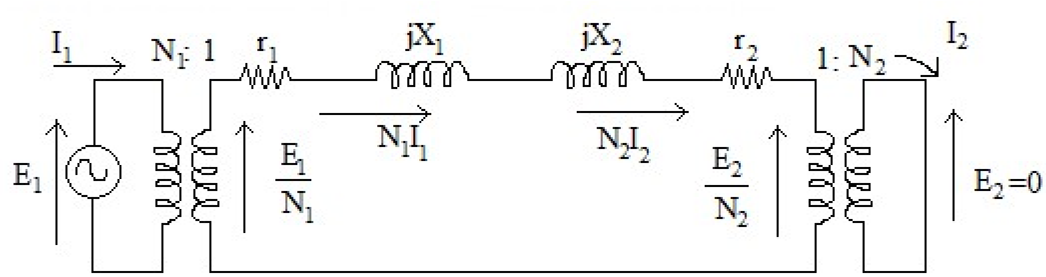


Fig 20: Diagram for short-circuit test of a transformer

Figure 19 shows an equivalent circuit of the two-winding transformer. The test is performed with first short-circuiting a winding then passing the voltage in the range of generally 1/10th that of rated voltage and observing the drop in voltage across the combined series winding, similar kind of test is performed with other winding [55]. After modeling a two-winding transformer in OpenDSS and performing the short-circuit test, we get the following results.

i/p %z modeled	Observed % z after test
1.0	1.07
2.0	2.03
3.0	3.03
4.0	4.02
5.0	5.02
6.0	6.01
7.0	7.01
8.0	8.01
9.0	9.0095
10.0	10.0078
15.0	15.0044
20.0	20.0050
25.0	25.0046

Table 6: Modelled and observed impedances for 2-wdg transformer

The column on the left side shows the values of the impedance used while modeling the transformer in OpenDSS, and the column on the right shows the value of impedance after performing the short-circuit test. We can see that value may differ mainly due to how OpenDSS models a transformer like some component of the magnetizing circuit. However, as the value of impedance increases, the value is almost equivalent to each other. A similar test can be carried with a 3-winding transformer, with the change that we need to perform this test with every two winding like 1-2, 2-3, 3-1, the circuit diagram for such test is:

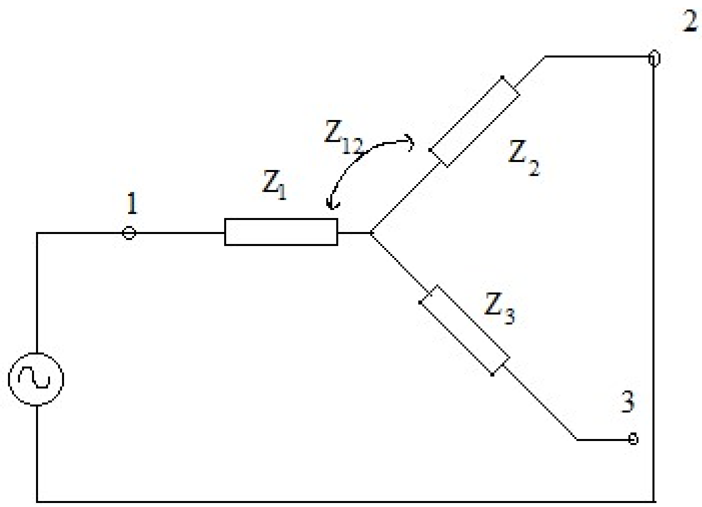


Fig 21: Diagram for short-circuit test of a 3-wdg transformer

The test results after performing the short-circuit test for a 3-winding transformer are:

Z12 i/p	Z23 i/p	Z13 i/p	Z12 obs	Z23 obs	Z13 obs
1	1	1	1.0772	1.0772	1.0781
2	2	2	2.0396	2.0396	2.0408
3	3	3	3.0267	3.0267	3.0277
4	4	4	4.0199	4.0199	4.0207
5	5	5	5.0162	5.0162	5.0171
6	6	6	6.0138	6.0138	6.0147
7	7	7	7.0108	7.0108	7.0131
8	8	8	8.0106	8.0106	8.0115
9	9	9	9.0095	9.0095	9.0105
10	10	10	10.0078	10.0078	10.0087
5	7.5	10	5.0162	7.5113	10.0087
2	3	4	2.0396	3.0267	4.0207
5	7.2	9.8	5.0162	7.2108	9.8095

Table 7: Modelled and observed impedances for 3-wdg transformer

After performing the short-circuit test of the 3-winding transformer, the modeled 3-winding transformer acts like real life transformer as it follows a similar nature in tests like short-circuit test. Hence, using the modeled transformer will represent a realistic transformer and provide us with the benefits of a 3-winding transformer.

Chapter 5: Results and Analysis

Simulations, as described in Chapter 4, were performed with the model. The results were arranged with various data visualization methods to understand better what is happening in the system. The following data visualization techniques are used:

- Percentile Charts-95^{th}
- Percentile Charts-99^{th}
- Line Charts for violators

For the sake of this chapter, different irradiation conditions are characterized as scenario-1, scenario-2, and scenario-3, were-

- Scenario 1: Clear Week
- Scenario 2: Cloudy Week
- Scenario 3: Very Cloudy Week

This chapter also provides observations of various cases and interpretations that we can concur with by our data.

5.1 Percentile charts for voltage and current distortion

As specified in standards, we need to perform only 99^{th} percentile short time measurement when the study has been done for one week. For simplicity, tables 8 and 9 are compared with the limits specified in standards to compare what kind of violations are made by the modeled solar farm.

Harmonic Numbers	Limits	%Contribution Clear Week	%Contribution Cloudy Week	%Contribution Very Cloudy Week
1	100	100	100	100
2	1	0.11168	0.21216	0.133501
3	1	0.000304	0.05834	0.03335
4	1	0.118487	0.12586	0.07360
5	1	0.151654	0.23278	0.09992
6	1	0.001362	0.25334	0.06819
7	1	1.173170	0.85473	0.12210
8	1	0.593381	1.45938	0.12850
9	1	0	0	0
10	1	0.230519	0.13334	0.06017
11	1	0.169396	0.12068	0.07869
12	1	0	0.04544	0.03007
13	1	0.056767	0.08929	0.06659
14	1	0.049104	0.09162	0.14267
15	1	0.000433	0.07131	0.05909
16	1	0.078309	0.28872	0.32026
17	1	0.035437	0.14145	0.15307
18	1	0.032504	0.13750	0.14273
19	1	0.030039	0.14667	0.15370
20	1	0.027933	0.18541	0.21609
21	1	0.026109	0.13678	0.12422
22	1	0.012500	0.28526	0.31543
23	1	0.023095	0.11353	0.13384
24	1	0.021831	0.12163	0.14369
25	1	0.010347	0.17605	0.19597
26	1	0.019665	0.27011	0.39795
27	1	0.018726	0.10375	0.0945
28	1	0.008933	0.15532	0.23043
29	1	0.008538	0.06103	0.05591
32	1	0.007516	0.14391	0.19215
34	1	0.006944	0.17152	0.22911
48	1	0.004256	0.00475	0.00371
THD_v(%)		1.37	1.89	0.91

Table 8: 95th Percentile chart for voltage distortion

Harmonic Numbers	Limits	%Contribution Clear Week	%Contribution Cloudy Week	%Contribution Very Cloudy Week
1	100	100	100	100
2	0.5	0.60315	1.46235	1.49333
3	2	0.00100	0.25016	0.25014
4	0.5	0.25035	0.35846	0.41343
5	2	0.20153	0.43201	0.44773
6	0.5	0.00100	0.27019	0.25360
7	2	0.30473	0.32792	0.38725
8	0.5	0.09870	0.36356	0.35451
9	2	0	0	0
10	0.5	0.19924	0.15389	0.13087
11	1	0.19958	0.16916	0.15426
12	0.25	0	0.06916	0.05352
13	1	0.10001	0.13849	0.10825
14	0.25	0.1001	0.13967	0.21287
15	1	0.00100	0.10463	0.08127
16	0.25	0.20159	0.40299	0.40730
17	0.75	0.10039	0.18665	0.18068
18	0.1875	0.10048	0.17076	0.15662
19	0.75	0.10058	0.17103	0.15709
20	0.1875	0.10069	0.20275	0.20601
21	0.75	0.10080	0.14015	0.11060
22	0.1875	0.05146	0.27374	0.26253
23	0.3	0.10103	0.10197	0.10419
24	0.075	0.10116	0.10220	0.10466
25	0.3	0.05064	0.13829	0.13357
26	0.075	0.10141	0.19822	0.25375
27	0.3	0.10155	0.07106	0.05636
28	0.075	0.05084	0.09916	0.12842
29	0.3	0.05092	0.03626	0.02909
32	0.075	0.05116	0.06812	0.08069
34	0.075	0.05133	0.06878	0.08251
48	0.0375	0.05289	0.10715	0.14579
THD_i(%)		0.905	1.855	1.908
TDD(%)		1.608	1.98	1.59

Table 9: 99th percentile chart for current distortion

Observations:

Table 7: Voltage Distortion, Violations are observed in the clear week and cloudy week scenario, with a clear week at harmonic number 7 and cloud week at harmonic number 8. No other violations are observed for this type of distortion. Table 8: Current Distortion, Violations are observed in all three scenarios, with the highest violations in the very cloudy week. Even order harmonics make all the violations in current distortion. No clear idea can be derived from table 7 and 8, other than data about violations.

However, the harmonic number observed to violate current distortions is not observed to cause any violations in voltage distortion. Similarly, no current distortions are observed to impact current violations for the same harmonic number. Due to the nature of even-order harmonics and flexibility given by standards around them, they are not considering a significant issue regarding distortions by the plant. Nevertheless, odd harmonics are considered an essential component due to their ability to change voltage waveform and impact systems.

5.2 Validation of Results-

Ensuring the data observed is correct, validation analysis was performed on the model. Impedance scan of the system was calculated for the same. Impedance scan will find the impedance of the network for various frequencies, short-circuiting the voltage sources and open circuiting the current sources. Impedance scan of system is shown in Fig.35

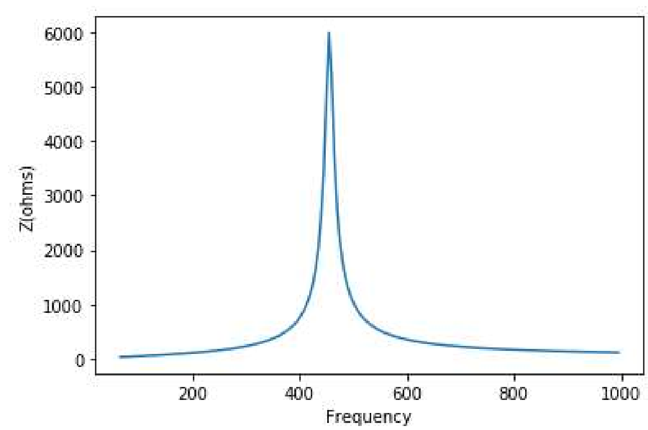


Fig 22: Impedance Scan of the Solar Farm Model

In the frequency scan shown in Fig 35, the network has the maximum resonance at frequency f = 455 Hz. This frequency is not overlapping with any harmonic current injected into the grid. Hence, no resonance condition is created in the circuit. For validating results shown in Table 7 and Table 8, harmonic number = 7^{th} is considered because it is the largest harmonic voltage distortion caused by an odd order. There is another even order (8^{th}) harmonic higher than this value, but even order harmonics are considered inconsequential as no significant impacts are observed in the system. Only voltage distortion is believed to significantly affect the grid, as the harmonic number having violations in current is not observed to reflect in voltage distortions. Hence, the 7th order harmonic is considered for in-depth analysis and validation. For validation, two cases were considered; here, one case is shown in Table 7, whereas data for the second case is derived from statistical analysis of time-series simulations; two cases are:

- Clear Day: PV Generation-100%
- Very Cloudy Day: PV Generation-20%

Cloud Coverage	**Clear**	**Very Cloudy**
P_{GEN}(%)	100	20
P_{GEN}(MW)	200	40
I_7(A)	$1.39\angle 29.84^0$	$0.337\angle 29.84^0$
I_1(A)	$456.159\angle 30.3^0$	$91.2\angle 30.3^0$
Z_7(Ω)	$1190.14\angle 76.51^0$	$1190.14\angle 76.51^0$
$V_7^{Calculated}$(V)	$1654.29\angle 106.35^0$	$401.077\angle 106.35^0$
$V_7^{Observed}$(V)	$1630.15\angle 106.53^0$	$395.585\angle 106.53^0$
THD_i	0.905	1.285
TDD	1.608	1.16
THD_v	1.39	0.381

Table 10: Comparison between Clear Day and Very Cloudy Day

For calculation in Table 9, values such as I_7, I_1, $V_7^{Observed}$ were observed from Tables 7 and 8. The value of Z_7 was observed from the frequency scan shown in Fig 35. The formula used for the calculation of $V_7^{Calculated}$ is as shown:

$$\overline{V_7^{Calculated}} = \overline{Z_7} \times \overline{I_7} \tag{7}$$

In equation 7, all the terms are in polar form, i.e., include magnitude and angles. Inverter injects more harmonic current at low PV generation. Hence, THD_i will be more for the cloudy case as the harmonic current will be more percentage of fundamental. For TDD, as the denominator is I_L, the cloud case will have less TDD than the clear case as the current will be less in magnitude than a clear case. For THD_v, the clear case will be higher than the cloud case due to the large voltage magnitude compared to the cloud case, whereas the magnitude of fundamental will be almost constant. In Table 9, $V_7^{Calculated}$ & $V_7^{Observed}$ values are comparable, signifying the model's accuracy.

5.3 Current distortions violators

The observation above reveals some harmonic frequencies which are violating the limits established by standards. These violations can be mitigated using low-to-high cost depending on the degree to which frequencies make violations. Example for three types of violations is shown below:

Low Violation

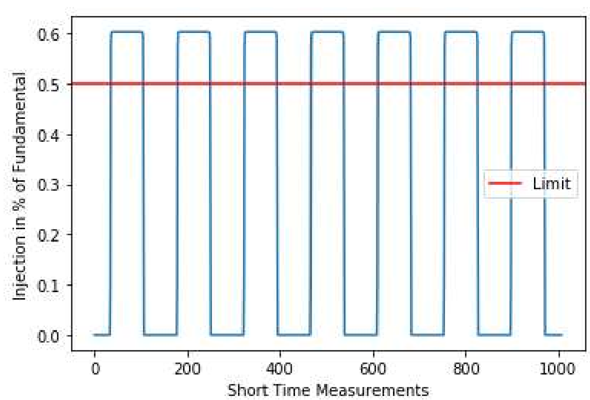


Fig 23: Line chart for a harmonic frequency with low violation

Medium Violation

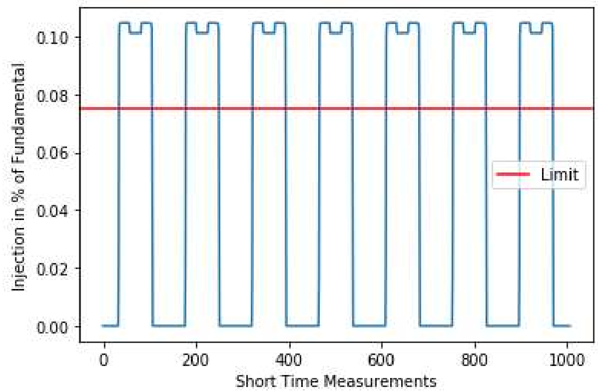


Fig 24: Line chart for a harmonic frequency with medium violation

High Violation

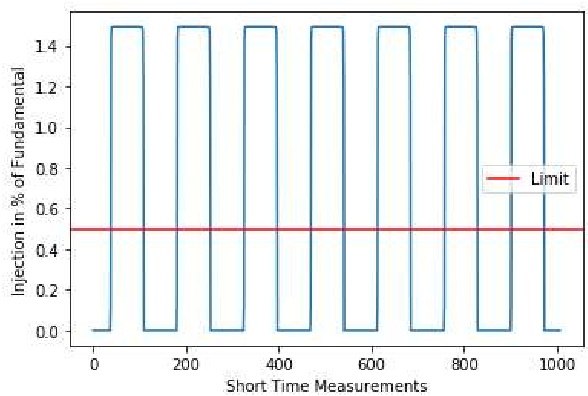


Fig 25: Line chart for a harmonic frequency with high violation

5.4 Total Demand Distortion

TDD is an accurate measurement in terms of harmonic current injections by the solar farm on an overall scale. Unlike individual current by harmonic frequencies, TDD is an absolute measure of current injections by all frequencies combine at PCC. THD_i is also used for finding current injections, but unlike TDD, THDi measures the distortion to fundamental current, which proves not to be an accurate measurement while calculating current injections; TDD finds the current injection to load current.

Finding such a load current is necessary for any study. We assume a constant load of the plant's nameplate capacity and calculate TDD based on that. For that purpose, the nameplate capacity of the plant is 200 MW, and the voltage rating is 230 kV,

$$I_L = \frac{200 \times 10^3}{\sqrt{3} \times 230} = 504\ A\ (approx.)$$

Hence, this current of 251 A was used as the load current to find TDD. Based on this data, the following graphs of TDD were observed for scenarios 1, 2, and 3.

TDD for the clear week-

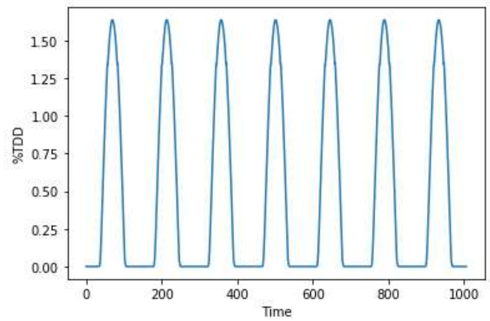


Fig 26: TDD for the clear week

TDD for the cloudy week-

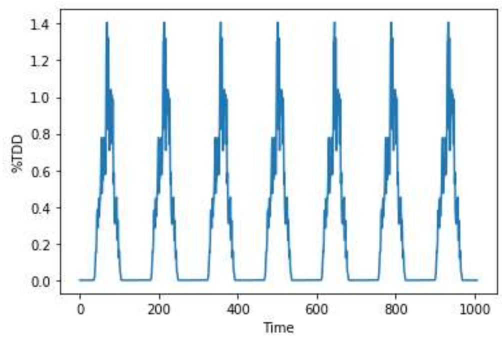


Fig 27: TDD for the cloudy week

TDD for the very cloudy week-

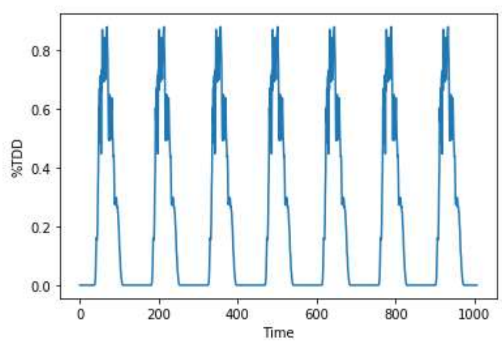


Fig 28: TDD for the very cloudy week

Observation: Based on TDD for all the scenarios, current injected by clear week are observed to be clean compared to cloud nature cases. The standard defines limits for TDD considering 99th and 95th percentile. All the cases have distortions well below the TDD requirement for the 99th percentile. In contrast, the scenarios are shown to violate the 95th percentile for some period.

5.5 Total Harmonic Distortion

THD_v or total harmonic distortion measurements are used for finding distortion caused by voltage. The formula for THD requires the calculation of injections and measures them to the farms the fundamental voltage. Following are the results of THD for various scenarios, THD for the clear week-

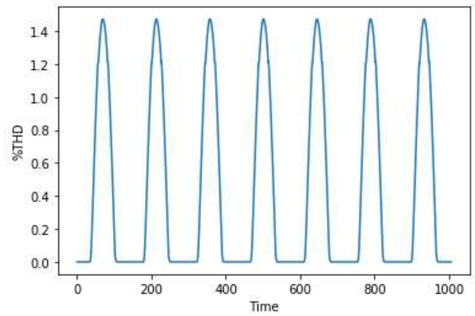


Fig 29: THD_v for the clear week

THD for cloud week-

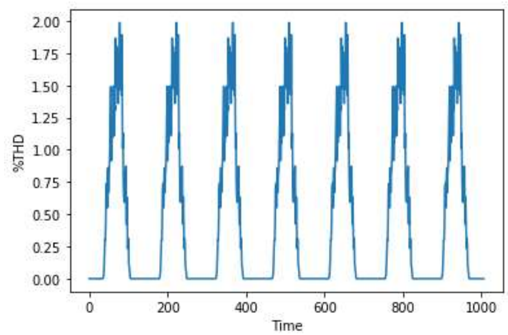


Fig 30: THD_v for the cloudy week

THD for the very cloudy week-

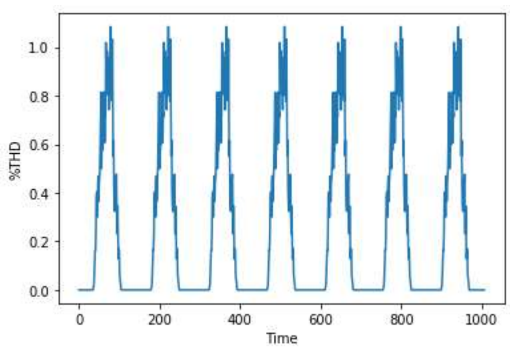


Fig 31: THD_v for the very cloudy week

Chapter 6: Conclusion

This thesis was developed to analyze harmonic distortions injected by the solar farms into the main grid and use the IEEE standards to evaluate such impact. In determining the effects, modeling, and simulation, tools such as OpenDSS and Python were used to model the solar farms and study such implications accurately. Irradiation was classified into three categories a clear week, cloudy week, and very cloudy week.

The results indicate the dependence of distortions on the nature of irradiation experienced by the solar farm. Generalizing the results is difficult due to each harmonic frequency's behavior in each scenario. However, the validation study performed in Chapter 5 provides a brief idea about total distortions. In this study, two cases with high irradiation in the clear week were compared with a very cloudy week with very low irradiation. The observations are summarized below:

$$\boldsymbol{THD_v^{Clear} > THD_v^{Very\ Cloudy}}$$

$$\boldsymbol{THD_i^{Very\ Cloudy} > THD_i^{Clear}}$$

$$\boldsymbol{TDD^{Clear} > TDD^{Very\ Cloudy}}$$

Inverters are observed to inject more harmonic current at lower solar irradiance, causing more individual harmonic violations at lower generations. This high current accounts for a higher percentage of fundamental. These statements are reflected in the validation study as well as Table 7 and Table 8. Violating harmonic frequencies are frequencies injecting more voltage or current compared to limits specified by standards. Several even order harmonics violators were observed to cause violations but are considered inconsequential as they were not observed to impact voltage distortion.

The results of this study confirm the existing claims in the literature with findings such as even order violations, irradiation dependence, and flexibility for limits for even-order harmonic frequencies. This thesis has tried to fill in gaps in the literature concerning harmonic studies of solar farms tools such as methodology for solar farm modeling on open-source software and providing simulation flowchart for effectively conducting time-series simulation studies. The results of this study are significant because they give a definite statement about the dependence of cloud cover and irradiation on voltage and current distortions.

Further investigation is recommended for having a more in-depth dependence on cloudiness and realistic scenarios. To better understand the implications of these results, future studies could address more versatile irradiation profiles. Further studies can also focus on mitigation techniques such as capacitor banks and potential conflicts in the grid, such as resonance conditions.

Appendices

Simulation-set complete code-
Available on Github Repo: https://github.com/Aaditya-Kulkarni/Harmonic-Studies-for-Solar-Farm

```
Created on Sat Nov 21 17:20:55 2020
@author: Aaditya Sunil Kulkarni
Program for simulation for investigation of harmonic current contribution by a Solar farm
"""
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
from datetime import datetime,date
import os
import win32com.client
dssObj= win32com.client.Dispatch('OpenDSSEngine.DSS')
FileLocation = os.getcwd()
MainDir= os.path.dirname(FileLocation)
Loadshape_data= os.path.join(MainDir,'Datasets')
d_loadshapes= os.path.join(Loadshape_data,'20190101')
dssText = dssObj.Text
dssCircuit = dssObj.ActiveCircuit
dssSolution = dssCircuit.Solution
dssElem = dssCircuit.ActiveCktElement
dssBus = dssCircuit.ActiveBus
dssText.Command =  r'compile C:\Users\kulka\Box\Research\Model\Model_200MW\Master.dss'
sourceName = 'Isource.PV_Inv_1'
dssCircuit.setActiveElement(sourceName)
MaxCurrent= dssElem.Properties('amps').Val
# Importing the file containing the irradiation data
#df= pd.read_csv((os.path.join(d_loadshapes,'z8520676.csv')))
#df= pd.read_csv(r'C:\Users\kulka\Box\Research\Datasets\20190101\z8520676.csv')
#df_new= pd.DataFrame(columns=['Data'])
## Select the date range for which you want the simulation running
#t0 = date(year=2019, month=1, day=1)
#t1 = date(year=2019, month=3, day=1)
#t2 = date(year=2019, month=3, day=7)
##t2 = date(year=2019, month=10, day=12)
#diff1 = (t1 - t0).days
#diff2 = (t2 - t0).days + 1
#df_new['Data']= df.iloc[diff1*1440:diff2*1440,2]
#df_new.reset_index(drop=True,inplace=True)
#df_new= pd.read_csv(r'C:\Users\kulka\Box\Research\Model\Synthetic_Irradiation\clearweek.csv')
#df_new= pd.read_csv(r'C:\Users\kulka\Box\Research\Model\Synthetic_Irradiation\cloudyweek.csv')
df_new=
pd.read_csv(r'C:\Users\kulka\Box\Research\Model\Synthetic_Irradiation\reducedcloudy_week.csv')
#max_irradiation = df_new['Data'].max()
# We need to make arrangement for max irradiation of that particular day according to needs of that day
```

```
total_length = df_new.shape[0]
divisions = int(total_length/1440)
maxs = []
selected_df = pd.DataFrame()
for i in range(divisions):
   selected_df= df_new.iloc[i*1440:(i+1)*1440,0]
   maxs.append(selected_df.max())
current_value = 0
number_inverters = 66
# Finding size of file or simulation time
simulation_time_steps= df_new.shape[0]
data = pd.DataFrame()
array = []
master_array = []
#simulation_time_steps = 700
# Function to find value of current for respective value irradiation
def find_current_value(irradiation):
   current_value = (irradiation) *  float(MaxCurrent)
   return [current_value]
def find_harmonic_value(irradiation):
   if irradiation < 0:
      irradiation = 0
   generation = irradiation
   # harmonic numbers of data available should be included in the matrix below
   harmonic_numbers=
[1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29,32,34,48]
   # Provide the value of inverter current contribution in the arrays below
   generation_33per=
[100,1.6,0.25,0.6,0.5,0.2,0.6,0.3,0,0.05,0.10,0,0,0.45,0,0.4,0.15,0.1,0.1,0.2,0,0.2,0.1,0.1,0.1,0.4,0,0.2,0,0.1,
0.1,0]
   generation_66per=
[100,1.4,0.25,0.25,0.4,0.3,0.2,0.4,0,0.2,0.2,0.1,0.2,0,0.15,0.4,0.2,0.2,0.2,0.2,0.2,0.3,0.1,0.1,0.15,0.1,0.1,0.0
5,0.05,0.05,0.05,0.05]
   generation_100per=
[100,0.6,0,0.25,0.2,0,0.3,0.1,0,0.2,0.2,0,0.1,0.1,0,0.2,0.1,0.1,0.1,0.1,0.1,0.05,0.1,0.1,0.05,0.1,0.1,0.05,0.05,
0.05,0.05,0.05]
   harmonic_current_contribution = []
   for n in harmonic_numbers:
      #    harmonic_numbers.index(n)
      x_interpolation = [0.0,0.33, 0.66, 1.0]
      y_interpolation=
[0.0,generation_33per[harmonic_numbers.index(n)],generation_66per[harmonic_numbers.index(n)],genera
tion_100per[harmonic_numbers.index(n)]]
harmonic_current_contribution.append(round(np.interp(generation,x_interpolation,y_interpolation),3))
   h = [int(i) for i in harmonic_numbers]
   h_contri = [float(i) for i in harmonic_current_contribution]
   return [h,h_contri]
```

```
def assign_values_currentSources(desired_current_value):
    for j in range(number_inverters):
        sourceName = 'Isource.PV_Inv_' + str(j+1)
        dssCircuit.setActiveElement(sourceName)
        dssElem.Properties('amps').Val = desired_current_value
def assign_capacitor_value(irradiation,number_of_capacitor):
    if irradiation<0.8:
        capacitor_value = 0
    if irradiation> 0.8:
        capacitor_value = 11500
    for j in range(number_of_capacitor):
        sourceName = 'Capacitor.Cap_' + str(j+1)
        dssCircuit.setActiveElement(sourceName)
        dssElem.Properties('Kvar').Val = capacitor_value
  def assign_harmonic_values_currentSources(harmonic_numbers,desired_current_value):
    spectrum= pd.DataFrame(columns=["harmonic_number","contribution"])
    spectrum["harmonic_number"]= harmonic_numbers
    spectrum["contribution"]= desired_current_value
#   Exporting the generated file to model
spectrum.to_csv(r'C:\Users\kulka\Box\Research\Model\Model_200MW\Spectrum.csv',index=False,header
=None)
 # Function to create a dataframe without the need to define each column for frequency
def create_dataframe(file):
    for k in file['Freq']:
        column_name = "Freq_" + str(k)
        phaseA_col = column_name
        data[phaseA_col] = 0
def convert_dataframe_to_array(file):
    iters = 0
    file_new = file.drop([' Harmonic',' VAngle1',' VAngle2',' VAngle3',' IAngle1',' IAngle2','
IAngle3'],axis=1)
    for k in file['Freq']:
        array.append(file_new.iloc[iters,:].values.tolist())
        iters = iters + 1
    master_array.append(array)
current_values = []
data_storage = []
for i in range(simulation_time_steps):
    print("************ Simulation Time Step************:",i)
#   max_irradiation = maxs[int(df_new.iloc[i,0]/1440)]
    desired_current_value= find_current_value(df_new.iloc[i,0])[0]
    [harmonic_numbers,harmonic_spectrum]= find_harmonic_value(df_new.iloc[i,0])
    assign_harmonic_values_currentSources(harmonic_numbers,harmonic_spectrum)
    assign_values_currentSources(desired_current_value)
    assign_capacitor_value(df_new.iloc[i,0],3)
    mName = 'HarmonicCurrentPCC'
    dssCircuit.Monitors.SaveAll()
```

```
    dssText.Command='set mode=HarmonicT'
    dssSolution.Solve()
    dssText.Command = "export monitors " + mName
    file= pd.read_csv("SolarFarm_Mon_harmoniccurrentpcc.csv")
    create_dataframe(file)
    convert_dataframe_to_array(file)
    array = []
master_dataframe= pd.DataFrame(master_array, columns=data.columns)
#list_test= arrange_data_ascending_order(master_dataframe['Freq_240'])
#print(list_test)
master_dataframe.to_csv(r'C:\Users\kulka\Box\Research\Model\Model_200MW\Data_1week_1min_resolu
tion_reduced_cloudy_week.csv',index=False)
```

SOLAR FARM DESIGN DOCUMENTS-1

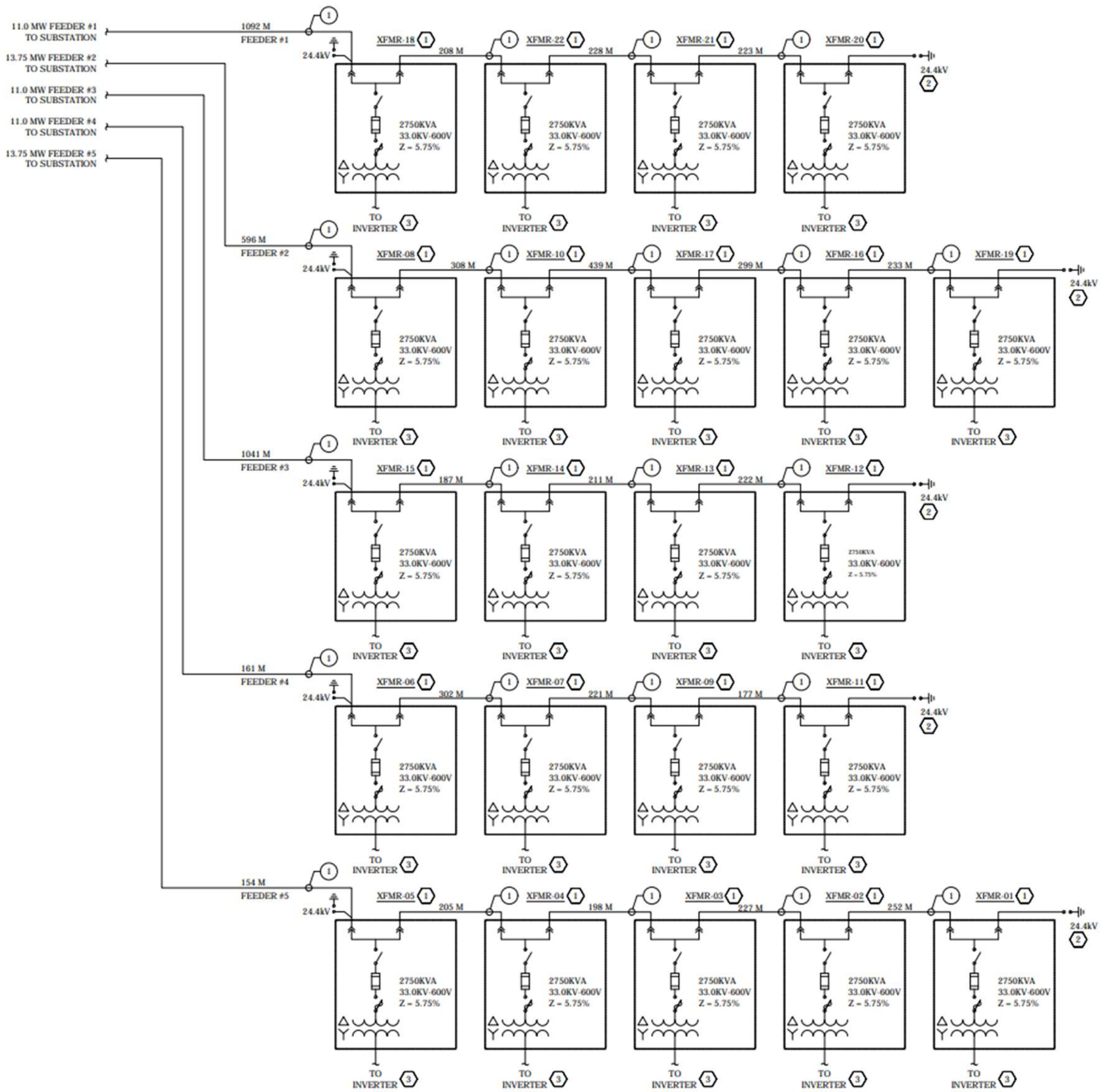


Fig 32:Solar farm detail plan

SOLAR FARM DESIGN DOCUMENTS-2

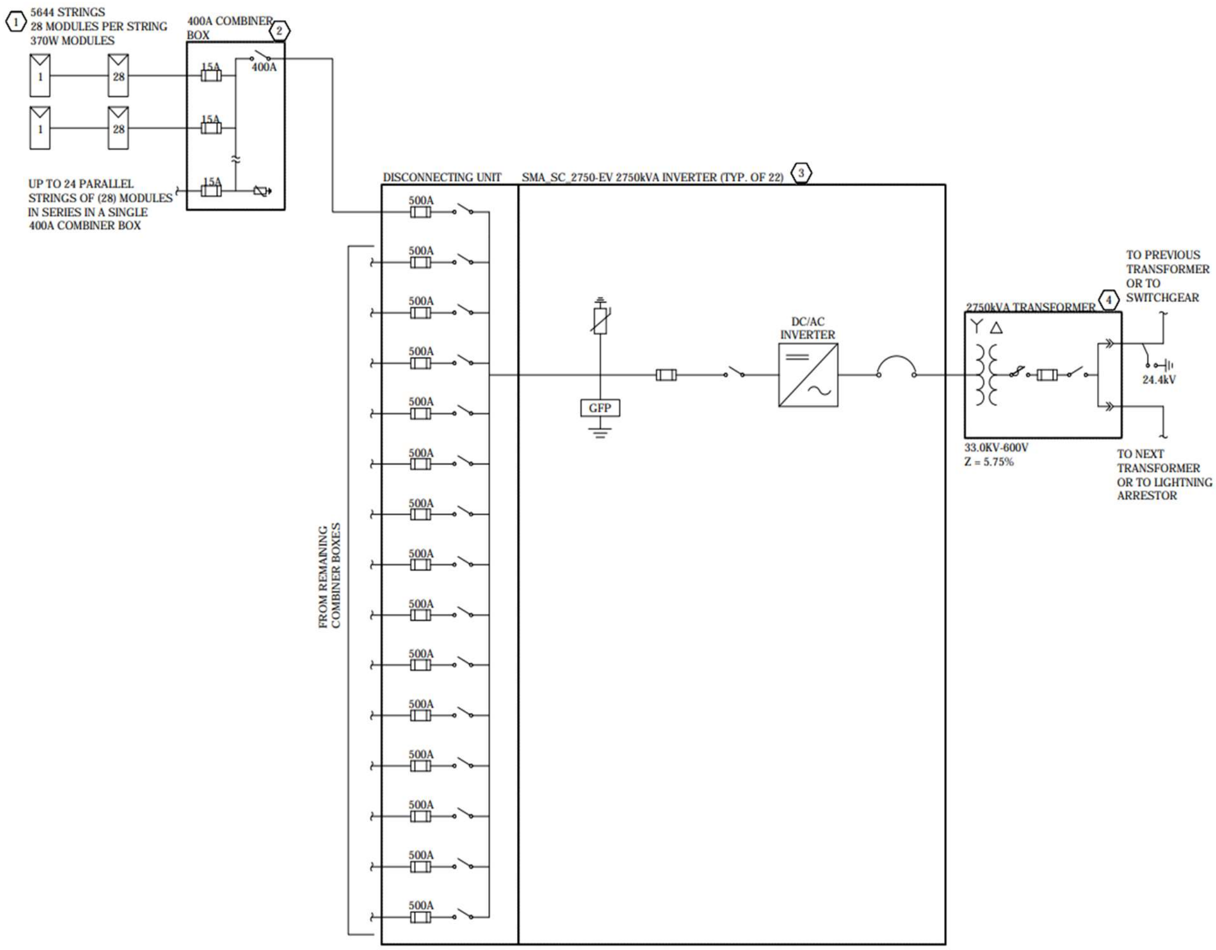


Fig 33: Solar farm array detail design

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